The development of visual attention and its connection with executive functions

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Thesis for the degree of Philosophiae Doctor

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Þroski sjónrænnar athygli og tengsl við stýrifærni

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Ágrip

Hefð hefur myndast fyrir því að rannsaka sjónræna athygli með sjónleitarverkefnum þar sem aðeins eitt markáreiti er til staðar í hverri umferð. Þannig finna þátttakendur áreitið, svara, leit er lokið og umferðin klárast. Þesslags rannsóknir hafa verið afar gagnlegar og aukið vitneskju okkar um sjónræna athygli gríðarlega, en þær eru að öllum líkindum ekki ákjósalegar til að kanna hvernig sjónræn athygli verkar yfir lengri tíma. Það er því vandkvæðum bundið að svo til öll líkön og kenningar um virkni sjónrænnar athygli eru komin frá rannsóknum sem nota aðeins eitt markáreiti, þar sem þær veita aðeins augnabliksglefsur af virkni athyglinnar á hverri stundu. Söfnunarrannsóknir eru góður valkostur við hefðbundin sjónleitarverkefni, þar sem þær gera okkur kleift að rannsaka hvernig þátttakendur leita að mörgum markáreitum innan um truflara. Með söfnunarverkefnum getum við rannsakað sjónræna athygli yfir lengri tíma með gagnvirku verkefni og fengið þannig upplýsingar um það hvernig athyglin færist yfir leitarskjáinn, auk þess að geta rannsakað val á markáreitum, bæði með tilliti til staðsetningar og gerðar þeirra. Í þremur rannsóknum hef ég skoðað þroska sjónrænnar athygli með söfnunarverkefnum, hjá börnum frá fjögurra ára og allt að fullorðinsaldri. Jafnframt hef ég borið frammistöðu í söfnun saman við þroska ýmissa undirflokka stýrifærni. Söfnunarverkefnið er lagt fyrir á spjaldtölvu og markáreiti geta verið skilgreind út frá einum þætti, svo sem lit, eða samsetningu tveggja þátta, svo sem litar og lögunar. Í greinum I og II sýndi ég fram á að söfnunarhæfni tekur miklum framförum á milli fjögurra og tólf ára aldurs, ekki aðeins í erfiðu samsöfnunarverkefni þar sem markáreiti eru skilgreind út frá samsetningu litar og lögunar, heldur einnig í einföldu þáttasöfnunarverkefni. Þessar niðurstöður eru í ósamræmi við rannsóknir sem notast við aðeins eitt markáreiti í hverri umferð, þar sem enginn munur finnst á þáttaleit hjá mjög ungum börnum og fullorðnum. Grein I sýnir einnig fram á að bæði þátta- og samsöfnunarhæfni tengjast frammistöðu á stýrifærniverkefnum, en tengslin á milli þessara ferla eru ekki þau sömu hjá börnum og fullorðnum. Í grein II sýni ég svo fram á að aldursmunur í söfnunarframmistöðu orsakast af stórum hluta vegna þroska stýrifærni. Í grein III skoða ég skipulag söfnunar, það er hvort ferill söfnunarinnar sé skipulegur yfir leitarskjáinn. Skipulag söfnunar fer vaxandi alveg upp til fullorðinsára, auk þess sem mælingar á skipulagi hafa tengls við aðrar hliðar söfnunarhæfni. Það bendir til þess að þroski sjónrænnar athygli sé að einhverju leiti háður skipulagshæfni. Niðurstöður þessara

rannsókna gefa dýpri innsýn í þroska sjónrænnar athygli en hægt væri að öðlast með rannsóknum sem aðeins nota eitt markáreiti í hverri umferð. Þannig undirstrika þær þörfina til að rannsaka sjónræna athygli út frá fleiri en einu sjónarhorni, svo hægt sé að skilja til fullnustu virkni hennar og þroskaferil.

Lykilorð:
Söfnun, þroski, stýrifærni, sjónræn athygli, skipulag.

Abstract

Visual attention has traditionally been studied with single-target search tasks where observers look for a single target and make a response, then the search is over and the trial ends. These studies have furthered our knowledge of visual attention tremendously, but they might not be ideal to describe visual orienting over time. It is therefore problematic that most all models of visual attention are derived from studies using a single target, only gaining a snapshot of attentional processing in each trial. Foraging research is an alternative to single-target search, where observers search for multiple targets among distractors. Foraging enables us to study attention over extended time periods with dynamic tasks, thus gaining insights into visual orienting over time, as well as target selection, both in terms of target location and characteristics. In a series of three studies, I investigated the development of visual attention with a foraging task, from children aged four years up until adulthood, and compared performance on various measures of foraging to executive functioning abilities. The foraging task is administered on a touch screen device and targets can be defined by either a single feature, such as color, or a conjunction of two features, such as color and shape. In papers I and II, I found that foraging abilities improve drastically between ages four and 12, not only in the more difficult conjunction foraging condition but also in feature foraging. Those results contradict findings from studies using only a single target per trial, where no difference is found between feature search of very young children and adults. Paper I reveals that both feature and conjunction foraging are connected with executive functions, but that these relations differ between children and adults. Paper II further reveals that age differences in foraging are largely mediated by the development of executive functions. In paper III, I look at the development of foraging organization, or the systematicity of the foraging path through each trial. I found that foraging organization continues to improve throughout childhood and adolescence, and that the organizational measures are connected with other aspects of foraging abilities, indicating that visual attentional development might be somewhat dependent upon organizational abilities. Taken together, these papers provide new insights into the development of visual attention, that would have been impossible to gain with studies using only a single target per trial. In doing so they highlight the need to study visual attention from various perspectives, so that we can gain a fuller understanding of its processes and their development.

Keywords:

Foraging, development, executive functions, visual attention, organization.

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Contents

List of abbreviations

2D = Two dimensional

3D = Three dimensional

ANOVA = Analysis of variance

ANT = Amsterdam neuropsychological tasks program

AttFlex = Attentional flexibility

AVE = Average variance extracted

C = Conjunction

CB-SEM = Covariance-based structural ecuation modeling

CFA = Confirmatory factor analysis

DCST = Dimensional card sorting tests

EF = Executive functions

F = Feature

Fig. = Figure

fMRI = Functional magnetic resonance imaging

GS1 = Guided search 1.0

HSD = Honestly significant difference

HTMT = Heterotrait-monotrate ratio

ITTs = Inter-target times

JASP = Jeffrey‘s amazing statistics program

ms = Millisecond

MS2D = Memory search 2D stimuli

MVT = Marginal value theorem

PAO = Percent above optimal

PCA = Principal component analysis

PFC = Prefrontal cortex

PLS = Partial least squares

PLS-SEM = Partial least squares-structural equation modeling

Prob.solv. = Problem solving

ROO = Response organization – objects

RT = Response times

SD = Standard deviation

SE = Standard error

SEM = Structural equation modeling

SPSS = Statistical package for the social sciences

ToH = Tower of Hanoi

ToL = Tower of London

TSP = Travelling salesman problem

VIF = Variance inflation factor

WCST = Wisconsin card sorting test

WM = Working memory

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List of original papers

This thesis is based on the following original publications, which are referred to in the text by their Roman numerals (I-V [as needed]):

I. Ólafsdóttir, I. M., Gestsdóttir, S., & Kristjánsson, Á. (2019). Visual foraging and executive functions: A developmental perspective. *Acta Psychologica*, *193*, 203-213.

II. Ólafsdóttir, I. M., Gestsdóttir, S., & Kristjánsson, Á. (2020). Age differences in foraging and executive functions: A cross-sectional study. *Journal of Experimental Child Psychology*, *198*, 104910.

III. Ólafsdóttir, I. M., Gestsdóttir, S., & Kristjánsson. Á. The development of foraging organization. Submitted for publication.

1 Introduction

A big part of our everyday life revolves around scanning the environment in search of something, whether it be looking for our car keys or phone before leaving the house in the morning, a friend at a packed restaurant, or scanning the playground when picking up our child from daycare. All of these tasks require visual attention. Visual attention is defined as the cognitive processes that amplify the salience of relevant objects in the visual field while filtering out irrelevant objects (McMains & Kastner, 2009). Visual attention has been studied extensively in the past decades and has been shown to affect most aspects of vision, from low level processing (Silver et al., 2007) to high level object recognition (Deco & Rolls, 2004), and might even be responsible for strengthening the interaction between goal-relevant low and high level areas of the visual cortex (Al-Aidroos et al., 2012). Visual attention has traditionally been studied with visual search tasks where participants look for a single target in a display, usually amongst one or more distractors (e.g. Treisman & Gelade, 1980; Trick & Enns, 1998; Wolfe, 1998). These tasks can vary in difficulty through numerous different manipulations, for instance target distractor similarity (Fifić et al., 2008; Scialfa et al., 1998), target presentation times (Juola et al., 1982; Lawrence, 1971), the number of distractor items (Bravo & Nakayama, 1992; Shen et al., 2000), distractor heterogeneity (Rosenholtz, 2001), or adding noise to the display (Allen et al., 1992). Observers are asked to indicate whether the target is present or absent and their response times and accuracy are measured. These tasks have many benefits, such as their ease of administration and interpretation of the data, and they have furthered our knowledge of the visual system and attention tremendously.

Most models and theories of visual attention are derived from research on single target search tasks. In these paradigms, observers look for a single target and make a response, then the search is over and the trial ends. Although they are analogous to various everyday tasks, such as the ones mentioned above, our visual world is not always this simple and most of the time we continue to scan and register our environment after a single instance of a target is found, for example while grocery shopping, looking at street signs while driving, or selecting coins for the meter. Therefore, dynamic paradigms that can capture attentional processes over time are necessary to understand how visual attention functions in our complicated and everchanging visual

world. Foraging research is an alternative to single-target search, which enables us to study attention over extended time periods with dynamic tasks. Foraging is traditionally defined as wandering in search of food or provisions (Merriam Webster collegiate dictionary, 1999) and the foraging behavior of animals has a long research history (see e.g. Bond, 1983; Dawkins, 1971; Ogden et al., 1983; Tinbergen, 1960). Foraging has in the past decades gained increasing interest in research of human visual attention (Kristjánsson, et al., 2014; Wolfe, 2013). Visual foraging paradigms involve searching for multiple targets amongst multiple distractors in the same display. This allows us to look at visual orienting over time as well as study how people choose between different target types (e.g. Kristjánsson et al, 2014), when they will leave a search patch (e.g. Wolfe, 2013), and how organized their search path is (e.g. Woods et al., 2013; paper III), to name a few of the many measures gained with foraging tasks (see Kristjánsson et al., 2019, for a review of foraging measures and methodology). Foraging tasks provide us with rich and multifaceted datasets which can further deepen our understanding of the processes of visual attentional mechanisms.

1.1 Models of visual search

As foraging research is a relatively recent development in studies on human visual attention, most models of visual search are built upon research on performance in single target search tasks. A common assumption is that cognitive processing can be divided into preattentive and attentive stages, as first suggested by Neisser (1967; see Kristjánsson & Egeth, 2020 for a historical overview). One of the most well-known models is without a doubt Treisman's feature integration theory.

1.1.1 Treisman's feature integration theory

In 1980, Anne Treisman published her influential feature integration theory. The theory states that certain feature dimensions are processed preattentively and in parallel, and that focused attention is required to bind different features together. Each feature dimension is preattentively encoded onto a separate feature map. Focused attention is then required to bind features from different feature maps together (see figure 1). In a series of experiments, she and her colleagues (Treisman & Gelade, 1980; Treisman et al., 1977) demonstrated that when a target item displayed among numerous distractors is defined by a single feature, it pops-out, making search quick and effortless. If a target is defined by a conjunction of two features, search becomes slow and effortful. Moreover, during search of a target defined by a single feature, the response

times were the same regardless of the number of distractors in the display. If the target was defined by a conjunction of features on the other hand, response times rose linearly as the number of distractors increased. They attributed these results to attention demanding feature binding. Feature binding could also explain so-called illusory conjunctions. When stimuli are presented for a very short time, or if attention is not focused on a set of stimuli, people may recall a blue triangle and red square as a red triangle and blue square. Treisman claimed that due to lack of attention, features from different maps had been erroneously bound together in the focused attention stage. Treisman revised her theory later to incorporate inhibition (Treisman & Sato, 1990), and a late selection state (Treisman, 1998) in an attempt to consolidate it with findings that were inconsistent with the original theory (see e.g. Egeth et al., 1984; Nakayama & Silverman, 1986; Steinman, 1987).

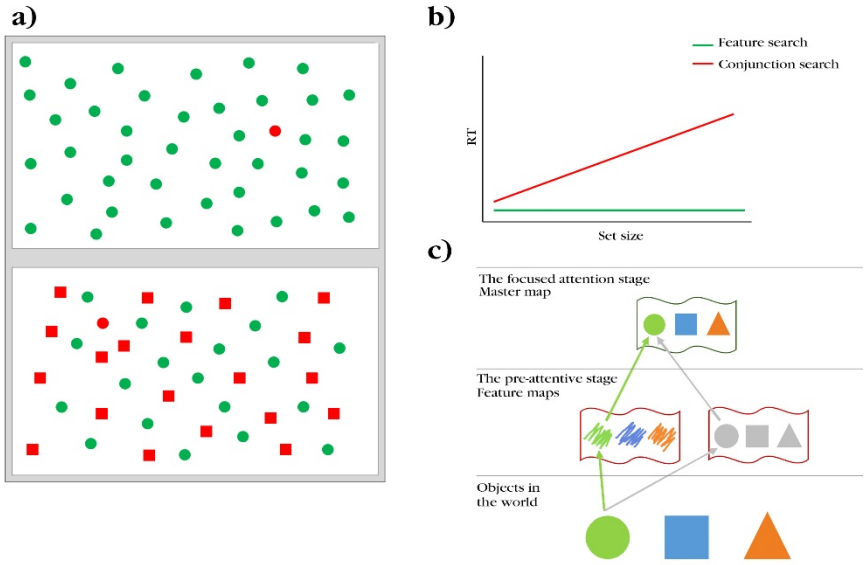

Figure 1. Treisman's feature integration theory. **Panel a)** shows search displays where only a single feature defines a target (upper) and where the target is defined by a conjunction of features (lower). The target in both displays is a red circle. Search is quick and effortless in the former, but requires attention and serial search in the latter. **Panel b)** shows search slopes in feature search (green line) and conjunction search (red line). RTs increase linearly as set size rises in conjunction search, but remains stable in feature search. **Panel c)** Objects in the world are pre-attentively encoded onto separate feature maps. The features require focused attention to bind them together. Image in panel c) adapted from: he.wikipedia.org, user: Alonelad.

1.1.2 Wolfe‘s guided search model

The guided search model (Wolfe, 1994; Wolfe et al., 1989; Wolfe & Gray, 2007) was presented as a modification of Treisman‘s feature integration theory, in an attempt to account for data that contradicted the predictions it made, such as shallow slopes in conjunction search (e.g. Egeth et al., 1984) and in triple conjunctions (Quinlan & Humphreys, 1987). The model builds upon feature integration theory and other two stage models that assume the existence of a preattentive, parallel process preceding a serial, attention demanding stage (e.g. Hoffman, 1978, 1979). The original guided search model states that unique stimulus features are processed in parallel by pre-attentive feature maps. This parallel process then facilitates top-down guidance of attention to likely targets, whereby each feature map excites the likely location of a target on a topographical activation map. If the target is for instance a red vertical bar, the color feature map will excite every location on the activation map where there are red stimuli, and the orientation feature map will excite locations of vertical stimuli. These activations will be added together on the activation map and the attentional spotlight will go first to the place with the highest activation.

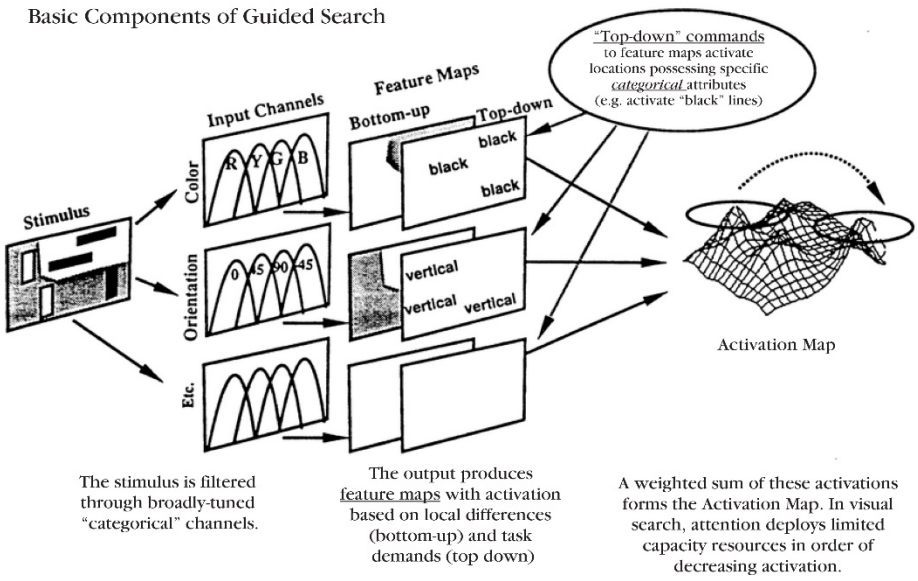

Figure 2. Wolfe’s original guided search model (GS1). Parallel feature maps process features of objects in the visual field. Locations of features relevant to the current search are excited in the activation map, guiding the spotlight of attention to the target item. Image reproduced from Wolfe (1994).

The model accounts for bottom-up processing as well, claiming that stimuli that are different from their neighbors will cause higher activation than stimuli that are similar to others, explaining pop-out effects in feature search. The model has been upgraded several times to account for new findings in the visual search literature, the latest version accounting for hybrid search and foraging for multiple targets (Wolfe et al., 2015).

1.2 Foraging

The foraging behavior of human participants has gained increasing interest in the scientific community in recent years. Visual foraging paradigms are easy to administer and provide rich datasets with a myriad of different aspects to analyze. Although scientists studying visual attention in humans have relatively recently discovered the possibilities of foraging research, it has a long tradition in animal research.

1.2.1 Animal foraging

Foraging studies originate in research on the foraging habits of animals. Research on animal foraging varies from ecological observations (e.g. Freitas et al., 2018; Ogden et al., 1983; Tinbergen, 1960) to laboratory experiments (e.g. Bond, 1983; Dawkins, 1971). A considerable body of research regards optimal foraging theory. Optimal foraging theory revolves around animals maximizing their energy intake while minimizing effort, in other words, foraging optimally for maximum gain. Researchers have attempted to describe animal foraging with mathematical models, such as Lévy flights (Humphries et al., 2012; Klages, 2018; Viswanathan, 2010) and Bayesian models (Olsson, 2006; Valone, 1991; Van Gils, 2010). An influential theory on patch leaving behavior is Charnov's (1976) marginal value theorem (MVT). The theorem claims that when animals forage in an environment where food sources are distributed in various patches, they will leave a patch as soon as the instantaneous collection rate drops below the average collection rate of the environment as a whole. The average collection rate is influenced by factors such as scarcity and conspicuity of the food items, as well as travel time between patches.

As well as studying how animals move through the environment during foraging, researchers have been interested in what food items they forage for. Tinbergen (1960) studied the feeding habits of tits during spring and summer in their natural habitat. He found that the selection criteria of prey did not fit a probabilistic model and hypothesized that the tits form certain search images for a few species of prey at a time and forage for those. A number of variables affect whether a certain species will evoke a search image, such as the size of

the prey, density, conspicuousness, and palatability. More conspicuous animals are more likely to give rise to search images, but if they are large and/or palatable enough, inconspicuous species can evoke search images. There is an interesting relationship between density and search images: When a certain species is sparse, the tits do not form search images and hunt them less than would be predicted by probabilistic encounters. When the density rises, a search image is formed and the tit forages for this species more than would be predicted. When the density rises even more, the consumption of this particular species falls again to a lower rate than would be predicted by chance encounters. Tinbergen's observations have sparked numerous investigations into these search images of various species of birds (e.g. Bond, 1983; Bond & Kamil, 1999; Dukas & Ellner, 1993; Dukas & Kamil 2000, 2001; Gendron, 1986; Lawrence, 1989), insects (e.g. Goulson, 2000), fish (e.g. White & Gowan, 2014), and mammals (e.g. Ostfeld, 1982) These studies have confirmed the existence of search images in the animals' mind. Search images in this literature can be equated with visual working memory representations in studies of human cognition and follow similar principles, for example in regard to priming (Bond, 1983), attention switching, and dual tasks (Dukas & Kamil, 2000, 2001). In an ingenious study on search images and switching behavior of chicks, Dawkins (1971) dyed grains of rice green and orange and distributed them on an orange background. The orange grains were thus cryptic and hard to find whereas the green rice was conspicuous and easy to find. She then recorded the feeding of chicks and found that they selected the grains in a non-random order, foraging for them in long runs, while still switching occasionally between the conspicuous and cryptic grains. In a series of studies, Dukas & Ellner (1993) and Dukas & Kamil (2000, 2001) show that blue jays have limited attentional capacities which affect their foraging capabilities. When they forage for cryptic prey they limit their attention to a single search image but if it is conspicuous they can frequently switch between different types of prey.

1.2.2 Visual foraging

In their review of optimal foraging research on animals, Pyke et al. (1977) divide foraging into four categories: 1) choice of food types, 2) choice of foraging patch, 3) time allotted in each foraging patch, and 4) movement patterns while foraging. All of these can be translated into research questions for visual foraging in humans: 1) which target to select, 2) which display or part of a display to select, 3) when to move to the next display, and 4) which foraging path to choose.

1.2.2.1 Runs

Bond (1982) was one of the first people to conduct a study of human foraging behavior. He had participants sort beads painted in four different colors into containers. The beads could either all look similar or have very distinctive colors. He then monitored both the sorting speed and the sorting sequence of the beads. He found that the participants foraged in non-random runs, switching between target types much less often than would be expected if switching happened at random. He also found switch costs in foraging; when participants did switch between bead colors, those transfer times were longer than transfer times within runs. Moreover, participants that switched more often between bead colors were less efficient in completing the task and made more errors than those who foraged in longer runs of same bead color. These results were particularly pronounced in the hard task.

Kristjánsson et al. (2014) were interested in how people switch between different foraging targets and introduced a new foraging paradigm, administered on a touch screen device. They hypothesized that the long runs seen in animals foraging for cryptic prey (Dukas & Kamill, 2000, 2001) might be due to mental load, but not solely to the conspicuity of the food items. They decided to use a modified version of a well-known single target search paradigm, feature and conjunction search, to manipulate mental load. The task was to find and tap on all targets while avoiding the distractors. The targets could be defined by a single feature dimension (color) or by a conjunction of color and shape (see figure 3 panel a). In both versions of the task, there were two types of targets and two types of distractors. In the feature foraging task, the targets could be red and green discs, and the distractors would then be yellow and blue discs, or vice versa. In the conjunction foraging condition, the targets could either be red squares and green discs, and the distractors green squares and red discs, or vice versa. They then tracked the number of runs per trial. A run is defined as the consecutive selection of the same target type, so every time the current target is of the same color, or color-shape combination as the previous one, the participant is continuing a run. As soon as the other type of target is selected, the current run is terminated, and a new run starts (see figure 3 panel c). In a foraging paradigm with 40 targets in two different colors, the minimum number of runs would be two, where every target of one type would be selected before the observer would start foraging for the next target type (see red line in figure 3, panel b). The maximum number of runs would be 40, which would occur if the observer never selects the same target type twice in a row, switching between target types with every tap on the screen (green line in figure 3 panel b). Lastly, if the target selection would

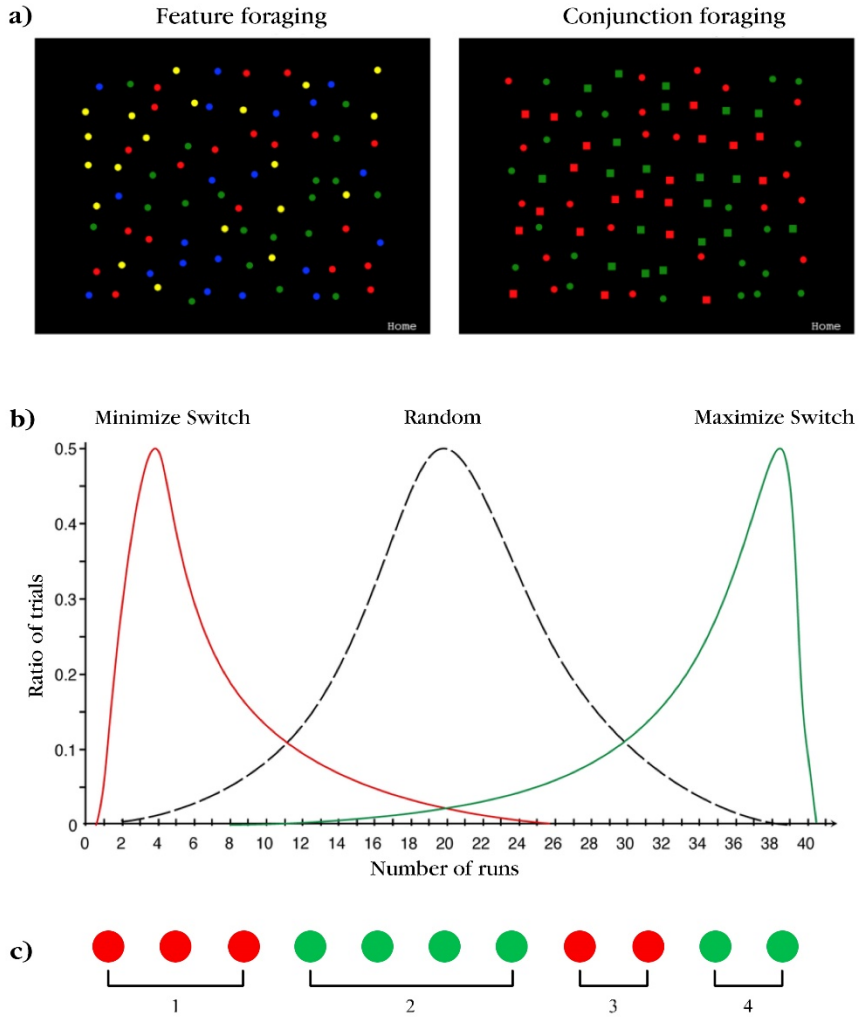

Figure 3. Feature and conjunction foraging. **Panel a)** shows the foraging paradigm from Kristjánsson et al. (2014). The feature foraging task is on the left and the conjunction foraging task on the right. Participants were asked to find and tap on all targets (e.g. red and green discs in the feature foraging task or red discs and green squares in the conjunction foraging task) and avoid the distractors. **Panel b)** shows three hypothetical run patterns. The red line shows how the number of runs would be distributed if participants would minimize switching between target types. Most trials would be completed in two runs. The green line shows the distribution of the number of runs if switching between target types would be maximized. If participants were to switch between target types in every instance of target selection, each trial would be completed in 40 runs. The dashed black line shows a random distribution of the number of runs per trial, the mean number of runs averages at around 20 runs. **Panel c)** is a visual representation of how the runs are counted. In this hypothetical scenario, the participant starts by selecting three red discs, which constitute the first run, the second run consists of four green discs, the third of two red discs, and so on until all targets have been selected. Image in panel b) reproduced from Kristjánsson et al. (2014).

happen at random, the number of runs should average at around a mean of 20 runs (see dashed line in figure 3 panel b). Kristjánsson et al. (2014) found that mental load did affect the foraging behavior of the participants. In the feature foraging condition, participants switched between target types at random but in the conjunction foraging condition, most participants rarely switched between target types, completing the majority of trials in only two runs.

A more recent study tested the flexibility of foraging behavior by setting time restraints on foraging (T. Kristjánsson et al., 2018). They found increased switching and reduced switch costs in conjunction foraging with time restraints, indicating that people are able to switch more efficiently between target types than previously believed. On a similar note, when participants are only rewarded for switching but not runs, they tend to switch often between target types (Wolfe et al., 2019). The pattern of completing conjunction foraging trials in two runs seems to be a strategic choice rather than a strict working memory capacity limitation, where observers are more willing to exert themselves for short bursts of time but opt for an easier way to complete the same task under no time constraints. Further evidence of run behavior being a foraging strategy rather than capacity limited is that no connection has been found between the number of runs and other cognitive abilities (Jóhannesson et al., 2017; Ólafsdóttir et al., 2016; see also papers I and II below). Other aspects of foraging, such as foraging speed (Ólafsdóttir et al., 2016; papers I and II), error rates (paper II), and switch costs (papers I and II), have been found to be related to cognitive functions in children and adults, but not the number of runs.

1.2.2.2 Inter-target times (ITTs)

Inter-target times (ITTs) in foraging are defined as the time that passes between each tap on a target item. ITTs are not uniform throughout foraging trials, and three distinct phases have been identified (T. Kristjánsson et al., 2020a; Ólafsdóttir et al., 2016; see also paper I). The largest part of each trial is characterized by a cruise phase, which is defined by rapid target selection. Distinct mid peaks occur midway through conjunction foraging trials and are attributed to switch costs, as most participants complete trials in two runs, switching only once, halfway through the targets on the display. All trials, in both feature and conjunction foraging tasks, end with a rise in ITTs, called an end peak. The end peak ITTS follow an interesting pattern where they are much larger in conjunction than feature foraging trials, and are stable regardless of set size in feature foraging, but grow linearly with set size in conjunction foraging, replicating a familiar pattern in single target search tasks

where response times grow linearly with set size (figure 4; T. Kristjánsson et al., 2020a). This might indicate that set size effects in single target search tasks only give a limited glimpse into what is happening during search and attentional orienting, as in all target collections leading up to the last one in conjunction foraging (excluding the mid peak), there are no differences in collection rates from feature foraging.

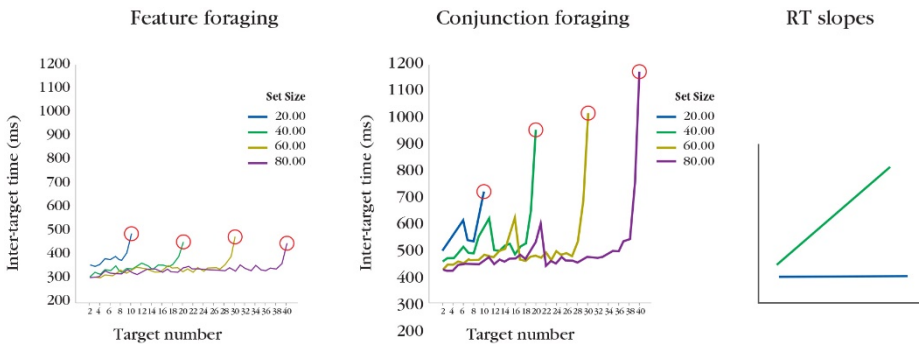

Figure 4. ITTs in a foraging task with various set sizes. The end-peak remains the same regardless of item number in feature foraging (left panel), whereas they grow larger with increased set size in conjunction foraging (middle panel). This resembles set size effects seen in single target search tasks (right panel). Image adapted from T. Kristjánsson et al. (2020a).

Results from studies of ITTs during foraging have challenged theories of visual attention, such as two stage processing models that differentiate between parallel preattentive stages and serial and slow attention demanding stages of visual search (Hoffmann, 1978, 1979; Treisman & Gelade, 1980; Wolfe, 1994), and slot models of visual working memory that claim that only a single template can be represented in working memory at each moment (see e.g. Olivers et al., 2011; Huang & Pashler, 2007). Kristjánsson & Kristjánsson (2018) studied the flexibility of visual working memory with a foraging task where they changed the number of target and distractor colors. They found that as the number of target categories rose, there was a gradual increase in inter-target times and switch costs. Those results indicating that working memory is a flexible entity, arguing against accounts of single-template capacities.

1.2.2.3 Patch leaving

Another interesting topic that can be investigated with foraging tasks is patch leaving, or when people decide to switch to the next foraging patch. In visual foraging paradigms, the visual display is often defined as a patch so leaving the present trial and starting a new one is equated with patch leaving (Cain et al., 2012; Fougnie et al., 2015; Á. Kristjánsson et al., 2020). In other studies, patch leaving is defined more literally, so that observers can choose a spot on a map to zoom into (Wolfe, 2013), or see an animation of an avatar walking to a new patch (Hutchinson et al., 2008).

In these paradigms, observers usually receive points for each target collected, and are free to switch between patches whenever they want. Their collection rate is measured as well as the point at which they leave the current patch. When the paradigms are simple and straight forward, observers tend to switch patches according to the marginal value theorem (Charnov, 1976), which claims that as soon as the instantaneous collection rate drops below the average collection rate, foragers should switch to a new patch (see e.g. Wolfe, 2013; Wolfe et al., 2016). When the tasks become more complicated, such as when the prevalence of targets varies (Cain et al., 2012; Wolfe et al., 2018), targets have different values (Wolfe et al., 2018), or when a temporal dimension is added to the paradigm (Fougnie et al., 2015), patch leaving starts to deviate from MVT predictions.

Not all studies using a straightforward foraging paradigm find that foraging behavior follows MVT principles. Using a slightly modified version of the foraging task from Kristjánsson et al. (2014), Á. Kristjánsson et al. (2020) found that patch leaving did not follow MVT predictions. Participants stayed within the same patch for much longer than the theorem predicted and despite large differences between other aspects of feature and conjunction foraging, such as runs and switch costs, patch leaving behavior was surprisingly similar between the two paradigms. They concluded that foraging depends upon too many different factors for it to be able to be described by a simple mathematical model.

When there are more than one target types in the foraging display, it is possible to study target selection. Run behavior can be defined as patch leaving of sorts, where one run of the same target type selection is considered a patch (Wolfe et al., 2016; 2018). Wolfe et al. (2018) studied both target selection and patch leaving in a hybrid value foraging task. Hybrid search is a paradigm when there are many possible target types but only a single target present on a search display. Subjects thus search through their memory while

searching through the display. Hybrid foraging is therefore searching for many instances of targets of many different types. Hybrid value foraging is a hybrid foraging task where targets are of both different prevalence and different value. They found that when targets had equal value but unequal prevalence, the more common targets were collected at a higher rate than would be predicted by random sampling, and the rarest items were collected at a lower rate than would be predicted, replicating studies on search images in the animal foraging literature (Tinbergen, 1960). In the uneven value, equal prevalence condition, the most valuable items were collected at a higher rate than would be expected by random sampling, and the least valuable items were collected at a lower rate. In the uneven value, unequal prevalence condition, where the highest value items were rare, and the items of the lowest value were the most common, foraging behavior varied more between participants. Some participants collected only the valuable items and completely left behind the less valuable items when switching to the next patch, while others collected some of the less valuable items, while still concentrating on the higher value items.

When looking at patch leaving in these three conditions, Wolfe et al. (2018) found that in the first two foraging conditions, patch leaving was in accordance with MVT, when the instantaneous rate of collection grew below the average rate, people switched to the next patch. In the uneven value, unequal prevalence condition on the other hand, some participants completely or mostly ignored the lower value items and switched to the next patch without collecting them, even though that meant that the instantaneous rate of return (in terms of points) was well above the average rate, leading to sub-optimal foraging. If analyses are focused on the collection rate of items regardless of their value, it becomes apparent that the participants are switching to the next patch when the instantaneous collection rate drops below average collection rate. Wolfe and colleagues propose a blueprint of a model of foraging behavior, where at least three different variables have to be taken into account: The potential target's distance from the current target, its value, and whether it is of the same type as the current one (see figure 5).

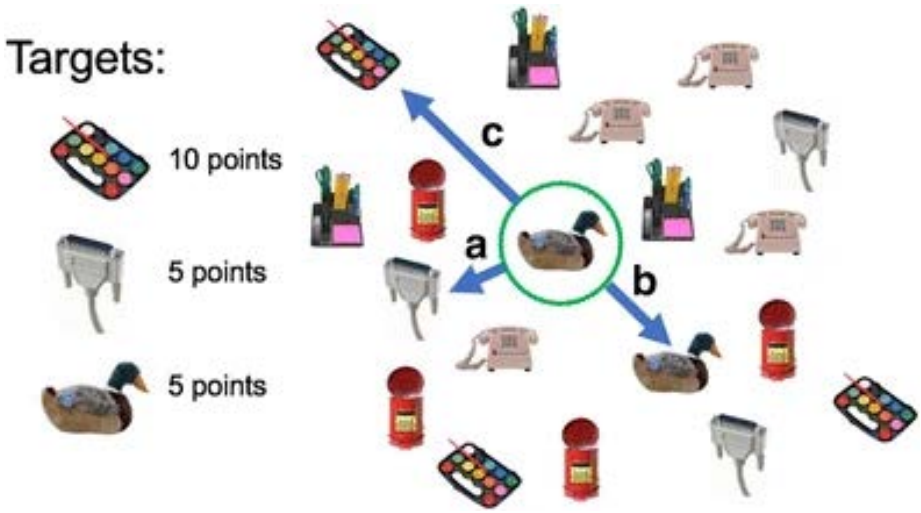

Figure 5. A blueprint for a model of foraging behavior. Three things have to be taken into consideration: **a)** The potential target's distance from the current target. People are more likely to select targets that are in close proximity to the currently selected target. **b)** The potential target's identity. If the potential target is of the same type as the current one, people are more prone to select it, as it has been shown that people are avoidant of target switching. **c)** The target value. More valuable targets are more likely to be selected. Image reproduced from Wolfe et al (2018).

1.2.2.4 Organization

A final aspect that can be investigated with foraging tasks, but not single target tasks, is the movement pattern throughout the trial. Measures of interest are for instance if and how well target collection is organized through the display (see e.g. T. Kristjánsson et al., 2020b; Woods et al., 2013; paper III), and where in the display observers initiate target collection (T. Kristjánsson et al., 2020b; Woods et al., 2013). Organization can be measured in various ways, such as with intertarget distances, the number of times the foraging path intersects itself, and with the best-r, which is the higher correlation coefficient out of the correlations between targets' selection number and their x-coordinates on the one hand and y-coordinates on the other. To date, only a handful of foraging studies have looked into this aspect of visual orienting. T. Kristjánsson et al. (2020b) studied foraging in a virtual reality environment. They found that observers were more likely to begin target collection in the bottom half of the display, and slightly more likely to forage from left to right, but depth did not affect target selection. The bottom half initiation bias indicates a figure-ground separation in a 3D environment. In their paper and pencil

cancellation task, Woods et al. (2013) found that at the age children start to read, they become increasingly likely to begin target cancellation on the top-left side of the display, indicating a reading bias. The 3D environment in Kristjánsson et al.'s study thus evoked a strong figure-ground separation effect which overrides the reading bias found in 2D displays. Woods and colleagues also investigated the development of search organization abilities from ages two to 18 years. They found that children grow increasingly more organized in their target cancellation paths up until age 12, where performance levels off.

The travelling salesman problem (TSP) is another way to look at foraging organization. This is a well-known topic in computer science where attempts are made to program computer software to find the shortest, or most optimal, path through a number of locations on a map. TSP is an np-hard problem which means that with increasing location numbers, the calculations become exponentially more complicated, and there are no effective computational solutions for it (Graham et al., 2000; Wiener et al., 2006). Nevertheless, people are remarkably efficient in solving TSP tasks, often selecting the most optimal way, and rarely surpassing it by more than 10% for the most complex problems (Graham et al., 2000; MacGregor & Ormerod, 1996, MacGregor et al., 1999; Vickers et al., 2003; Wiener et al., 2007). These tasks give insights into the extraordinary organizational abilities of humans, but they differ from foraging tasks in some respects, such as that there are no distractor items and people are asked to find the most optimal path through the items. In foraging research, the main interest would be whether people intuitively opt for the most efficient path through the display.

1.3 The development of visual attention

Since foraging research is a relatively recent development in the study of human visual attention, almost everything we know about how visual attention develops through childhood comes from studies using a single target search task. Below is a review of what these studies have revealed about the development of visual attention from infancy to adolescence.

1.3.1 Infants

Infants can localize a target which appears in their peripheral visual field as young as one month old (Aslin & Salapatek, 1975) or even from birth (Harris & MacFarlane, 1974). Infants between ages one to four months have difficulty looking away from a stimulus they are fixating and often exhibit long periods of staring. They are especially unlikely to disengage from a central stimulus and shift their gaze to a peripheral one. These disengagement difficulties increase

from birth up until one month of age, but from age two months their disengagement becomes increasingly efficient. By four months, infants can engage and disengage their attention rapidly and effortlessly (see Hunnius, 2007 for a review). For obvious reasons, it is impossible to measure RTs and accuracy of the visual search abilities of infants. Researchers have therefore used various ingenious ways to investigate infant visual attention. In preferential looking paradigms (see e.g. Fantz, 1958) the infants are presented with two different stimuli. It is then recorded for how long the infants look at each stimulus, if they look at one stimulus for a significantly longer time than the other, it is assumed that the infants can discriminate between the two. Colombo et al. (1995) tested pop out in three and four-month-old infants with a preferential looking paradigm. Two stimulus arrays were presented to the left and right of the midline of the visual field, for five seconds. In one of them, all stimuli were the same, in the other one, there was one discrepant stimulus. It was then recorded which stimulus array the infants fixated. In the majority of trials, infants fixated the array with a discrepant stimulus. Colombo and colleagues therefore concluded that infants do exhibit pop out. Sireteanu & Rieth (1992) tested infants' ability to detect differences in blob size and line orientation with a preferential looking task. They found that by two months, infants could distinguish between different sized blobs, but the ability to detect different line orientations appeared by age 12 months. Bhatt et al. (1999a) used the preferential looking paradigm to investigate infants' ability to perceive a textual discrepancy in a display. They found that infants were able to detect these discrepancies induced by changes of single features, but not if they were induced by changes in the conjunctions of features. They concluded that these results indicate a mature preattentive system to process features, but the attentional system required for processing feature conjunction has not yet developed by age 5.5 months.

A similar method is the habituation paradigm. It consists of repeatedly presenting a stimulus to an infant, and then presenting a novel stimulus. If the infant's looking duration is longer for the novel stimulus than the old one, it is assumed that the infant can distinguish between the two. Bertin & Bhatt (2001) used a habituation task on infants and found that stimulus similarity and heterogeneity have the same effect on infant and adult object segregation ability. Rovee-Collier et al. (1992) investigated infants' visual abilities with a mobile kicking paradigm (see figure 6). The infants' legs were connected to a mobile with a ribbon. They were trained to kick when certain stimuli were arrayed on the mobile and not when other stimuli were presented, that is, the ribbon was removed so the mobile did not move when they kicked, so

eventually they gave up kicking when nothing happened to the stimuli. Once the infants had been trained they were tested first on retention and it was found that they distinguished + signs from Ls and Ts with a 24-hour delay. With only a one hour delay they distinguished between the Ls and Ts. They were then tested with a unique object presented with six other simple stimuli (textons, see Julesz, 1981). If the unique object was the one they had been trained on, they kicked, but if it was a novel object they withheld a response. They did not respond if the number of training objects was increased to three among four novel stimuli. Rovee-Collier and colleagues concluded that this indicated pop out in visual attention, as has been established in adults.

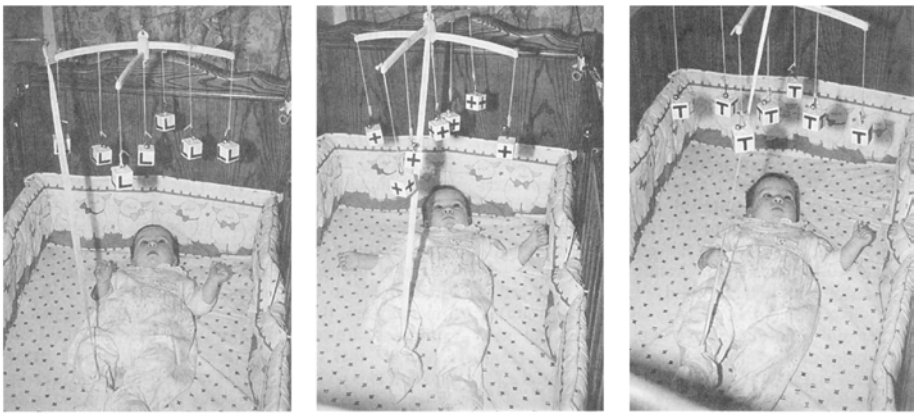

Figure 6. The mobile kicking paradigm. Image reproduced from Rovee-Collier et al. (1992).

Although other researchers had used eye tracking to study infant gaze shifting (e.g. Hunnius & Geuze, 2004) and scanning behavior (e.g. Aslin & McMurray, 2004), Adler & Orprecio (2006) were the first to investigate pop out in infants via saccade latencies. They presented the infants with both target present and target absent trials and found that in target present trials, saccade latencies stayed the same as set size increased, but increased linearly with set size in target absent trials. They administered the same test to adults and the results were close to identical. They concluded that three-month-old infants exhibit pop-out on a millisecond scale, the same as adults.

1.3.2 Toddlers and preschool aged children

In contrast with the myriad of studies on the visual attention of infants and older children, there seems to be a gap in the literature when it comes to studies of the visual search abilities of toddlers and preschool aged children. Although children at this age are able to follow simple instructions and press a button, getting them to respond quickly and accurately comes with its own set of problems. The tasks have to be very engaging and interesting to the children and cannot take more than a few minutes to administer to avoid confounding search abilities with fatigue, lack of motivation or interest. Gerhardstein & Rovee-Collier (2002) managed to do that when they tested children aged 12 to 36 months on feature and conjunction search tasks in two separate experiments. The stimuli in the experiments were red and green cartoon dinosaurs. In the feature search task, one of the dinosaurs was a different color than the others. In the conjunction search task, there were two types of dinosaurs ("Dino" and "Barnette"). Then the target item could for instance be a green "Barnette" amongst green "Dinos" and red "Barnettes". The children were sat in front of a touch screen on the lap of a caregiver and had to find and press the target dinosaur displayed amongst a number of distractor dinosaurs. When they made a correct response, an enticing sound was triggered, and four animated objects appeared and danced around the screen for 1 second. This was done to keep the children engaged and motivated towards finding the target. In experiment 1 they found that all the children had flat search slopes in the feature search task, but the 12-month-old children were unable to complete the conjunction search task. The 24 and 36-month-old children were able to find the target dinosaur but had steep search slopes in the conjunction search task. In experiment 2 they raised the age limit of participants to 18 months and found again that all children had flat search slopes in the feature search task and steep search slopes in the conjunction search. They concluded that the mechanisms mediating feature and conjunction search were different. The process underlying feature search was more primitive and therefore mature by infancy, whereas by 12 months, conjunction search mechanisms are not yet developed enough for the children to perform a conjunction search task like the one in their study. The ability to perform this type of conjunction search appears between 12 and 18 months.

Thompson and Massaro (1989) got similar results when they compared the visual search of 4 and 5-year-old children and adults and found that feature search performance was comparable between the preschoolers and adults in terms of search slopes, but the children's search slopes in conjunction search were much steeper than adults'. They concluded that children's feature

integration is slower than adults'. Additionally, when made to estimate the likeness of stimuli to previously studied squares that differed on two dimensions; size and brightness, the children tended to focus on a single feature more than the adults, and the adults seemed to have a more fine grained processing of the stimulus dimensions.

In a recent study, Gil-Gómez de Liaño et al. (2020) studied unique search abilities of children, adolescents, and adults between ages four and 25. The unique search task is designed to simulate real world search in the form of a video-game like task. The targets are cartoon images of real objects and each target object is only presented once. The game was set up to be a treasure search, where observers helped the protagonist to find stolen items and retrieve them from the pirates. They found that the first thing to develop was search accuracy, which improved substantially between four and five years of age. Just like in conjunction search tasks, the search slopes of the youngest children were much steeper than the search slopes of older children and adults. Interestingly, search slopes were steeper for five than four-year-olds, indicating a speed-accuracy trade-off in the performance of the youngest children in the study.

1.3.3 School aged children and adolescents

When children have reached school age, they are able to take part in visual search experiments without much trouble. Their attention span is shorter than adults', so it is necessary to keep experimental sessions shorter than for adult participants. Keeping them engaged with experiments in the form of serious games would be preferential, to capture attention and keep them motivated, but it is not as necessary as when testing toddlers. Although young school aged children are capable of participating in experiments designed for adult participants, it is important to keep in mind that children's information processing is slower than in adults (see Kail, 1991 for a review), so baseline search times do not give information about developmental trends of visual attention. Many researchers have compared the search slopes of children of various ages and adults to gain insights into visual attentional development. When performing feature search, school aged children's search slopes are flat, which mirrors the results found in experiments on adults. In conjunction search tasks, however, the search slopes of six-to-seven-year-old children are much steeper than is found for adults and older children. Children aged nine to ten also have steeper search slopes than adults, but they are more gradual than is seen in younger children (Donnelly et al., 2007; Merrill & Lookadoo, 2004; Trick & Enns, 1998). A few studies have found less drastic differences between

search slopes of children and adults, but the error rates of children in those studies are higher than in adults, which may indicate a speed-accuracy trade-off (see e.g. Hommel et al., 2004; Lobaugh et al., 1998). Search slopes reach adult efficiency between ages 14 and 16 (Gil-Gómez de Liaño et al., 2020), but response times (RTs) in complex search tasks continue to decrease at least up until age 19 (Burggraaf et al., 2018). Burggraaf et al. (2018) studied conjunction search in adolescents while tracking their eye movements. They found that visual search became more efficient between ages 12 and 19, where search became faster while accuracy remained stable. This increased efficiency was due to stimulus fixation times. No age differences were found in neither the number of fixations per trial nor the selection of fixation locations.

Why are children's search slopes steeper than adults'? Trick and Enns (1998) administered a series of increasingly complicated visual search tasks to children from age six, young adults, and senior adults (aged 72), in an attempt to tease apart different aspects of visual search tasks. The first task consisted of a single item presented in a fixed location, and observers had to respond whether it was a target. There was no age difference found with regard to how much responses slowed down when the target item was defined by a conjunction of features compared to a single feature. In the second task the single item appeared in a random location on the screen. Again, there were no age differences in the effect of conjunctions compared to features. These results rule out eye movement speed, reflexive orienting towards new stimuli, and peripheral acuity as explanations for age differences in visual search. When a single distractor item was presented alongside the target item, it affected the performance of the six-year-old observers, in both the feature and conjunction tasks, but no other age group (see also Hommel et al., 2004; Merrill & Conners, 2013). Adding more distractors affected the conjunction search performance of both the youngest children and the senior adults, indicating that engagement and disengagement from stimuli is still maturing up until age ten and regresses in old age.

Merrill & Lookadoo (2004) investigated conjunction search in children aged seven and ten and compared them with young adults. They found that in a standard conjunction search task, children were less effective in finding the target item, evident from steeper search slopes than that of adults. The seven-year-old children were also less effective than the ten-year-olds. These results are in accordance with other studies of children's search slope effects. They then restricted a subset of the distractor items to a certain number, that is, distractor set size could be 4, 8, 16 or 32, but one type of distractors (black squares) was always restricted to for instance two while the number of the

other distractor type (grey circles) varied. When they restricted a subset of the distractor items in this way, all age groups showed more efficient search, the children nevertheless still less efficient than adults. When the number of the restricted distractor type was kept low, the children benefitted more. When there were only two black squares in the display, the ten-year-old children's search slopes were equivalent to those of adult participants, but as soon as the number of restricted distractor items became four, their search became less effective than that of adults. Merrill & Lookadoo (2004) concluded that children are able to restrict search to a part of the stimulus array, but to a lesser extent than adults, resulting in less effective search and steep search slopes.

1.3.4 The development of visual attention: Summary

Young children and infants as young as two-months-old exhibit pop-out effects in feature search tasks on a millisecond scale (Adler & Orprecio, 2006; Gerhardstein & Rovee-Collier, 2002; Sireteanu & Rieth, 1992). When it comes to conjunction search and search of more complex stimuli, young children exhibit high error rates (Gerhardstein & Rovee-Collier, 2004; Gil-Gómez de Liaño et al., 2020), and steep search slopes, which gradually decrease up until 14 or 16 years, where they have reached adult efficiency (Gil-Gómez de Liaño et al., 2020; Merrill & Lookadoo, 2004; Trick & Enns, 1998). The speed of search continues to increase up until age 19 and can be attributed to the length of fixation time on each stimulus (Burggraaf et al., 2018). These results have led researchers to propose different mechanisms that are responsible for feature and conjunction-based processing. The mechanisms responsible for feature processing mature in infancy but the ones that are used for the processing of conjunctions of features or more complex stimuli are developing throughout childhood (see e.g. Bhatt et al., 1999a, 1999b; Bertin & Bhatt, 2001; Gerhardstein & Rovee-Coller, 2002). Since children's difficulty with conjunction search can be attributed to their difficulty with ignoring distractors (Trick & Enns, 1998), engaging and disengaging attention from stimuli (Hommel et al., 2004; Trick & Enns, 1998), and guiding search to a particular subset of the stimulus array (Merrill & Lookadoo, 2004), the mechanisms responsible for conjunction search might be executive functions.

1.4 Executive functions

Executive functions (EF) are a multidimensional construct that consists of separate but interrelated processes that are responsible for goal-directed behavior (Alexander & Stuss, 2000; Miyake et al., 2000; Pureza et al., 2013; Stuss & Alexander, 2000; see Baggetta & Alexander, 2016; Best & Miller,

2010; Best et al., 2009, for reviews). Because of their complexity, there is an ongoing debate about the exact nature of EF, and definitions can vary substantially (see Baggetta & Alexander 2016, for a systematic review). Originally, the debate revolved around whether EF is a single construct that could be described as a central executive that monitors, organizes and controls other cognitive functions (e.g. Baddeley, 1992, 1996; Burgess & Shallice, 1996; Della Sala et al., 1998; Repov & Baddeley, 2006; Shallice, 1990), or multiple components, that may or may not be interrelated (e.g. Miyake et al., 2000; Stuss & Benson, 1986; Walsh, 1978). A general consensus has been reached that EFs are multidimensional; Baggetta & Alexander (2016) found in their systematic review that 79% of studies defined them as such, while the remaining 21% defined them as unidimensional or did not discuss their dimensionality. Researchers tended to still disagree on which components EF is comprised of, how many they are, and how these components relate to each other, so much that Baggetta & Alexander (2016) found 48 different models of EF in their review, and 39 different processes suggested as components of EF, a large percentage of them only mentioned once, while another review found more than 15 suggested components (Best et al., 2009). Although this debate is still ongoing, most researchers agree that three components: inhibition, attentional flexibility or shifting, and working memory are core components of executive functions (e.g. Best et al., 2011; Brocki & Bohlin, 2004; Huizinga et al., 2006; Miyake et al., 2000; Pureza et al., 2013; Wu et al., 2011).

Inhibition is the most frequently mentioned component of EF (Baggetta & Alexander, 2016) and refers to the ability to inhibit or stop an automatic or prepotent response (Best et al., 2009; Lee et al., 2013; Miyake et al., 2000; Wu et al., 2011). According to Best et al. (2009; see also Best & Miller, 2010), inhibition is not a unitary construct and most inhibition task can be divided into simple and complex inhibition tasks. In simple tasks, it is only necessary to suppress a dominant response which should measure the purest form of inhibition, but in more complex tasks, it is necessary to remember an arbitrary rule and/or produce an alternative response. In those tasks, inhibition can be confounded with working memory or other processes.

Working memory refers to being able to keep in mind and manipulate information or mental representations (Davidson et al., 2006; Wu et al., 2011; Lee et al., 2013; Sander et al., 2012; Tsubomi & Watanabe, 2017), and attentional flexibility or shifting is the ability to switch between two or more alternative mind sets, mental operations or even response sets (Baggetta & Alexander, 2016; Davidson et al., 2006; Lee et al., 2013; Wu et al., 2011).

Attentional flexibility is believed to rely upon working memory and inhibition, because it requires the ability to remember different rules and stop or inhibit a previous response set in order to switch over to adhering to new rules or a different response (Best & Miller, 2010; Davidson et al., 2006). Together, these three processes seem to enable cognitive control and goal-directed behavior.

1.4.1 The Miyake model

The most influential model of executive functions is most likely Miyake and colleagues' (2000) model. They used confirmatory factor analysis (CFA) to answer the question whether executive functions consisted of one, two, or three factors, and whether these factors were intercorrelated or not. By using various measures of each proposed component, they were able to extract the common variance of these tasks and assign them to latent factors. After reviewing the literature on executive functions, they set the three latent factors to be inhibition, working memory, and shifting, and used three measures for each component (see figure 7).

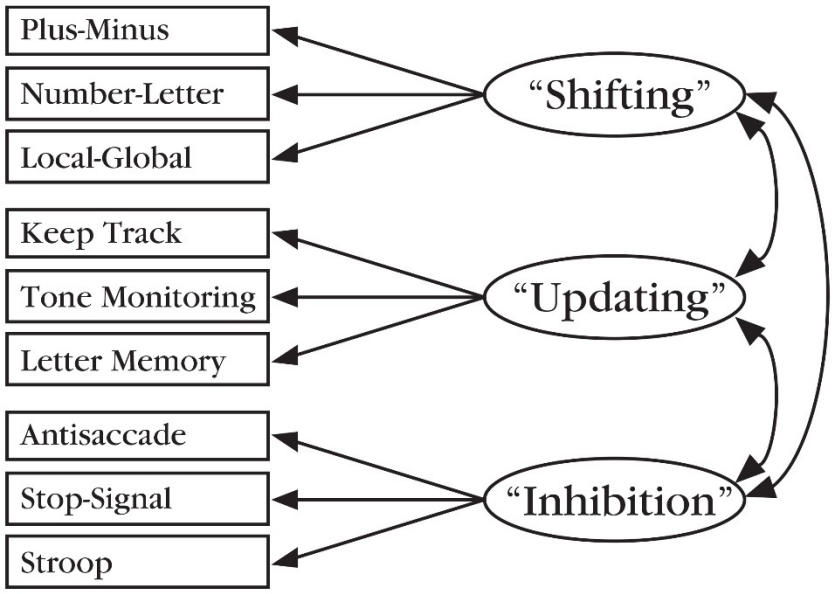

Figure 7. The Miyake model of executive functions. Each task is represented as a manifest variable on the left. Each manifest variable loads onto one latent factor, shown in three ellipses. The latent factors are all separate but intercorrelated, shown with bidirectional arrows connecting them. Reproduced from Miyake et al. (2000).

By using CFA, they were able to construct several factor models and then find the one that best fit the data. The model that provided the best fit was the full three factor model, where latent variable intercorrelations were allowed to vary freely. This model preceded models where: 1) no correlation was allowed between factors, which would have meant that the three factors were completely independent of one another, 2) all correlations between latent factors were fixed at 1, resulting in a single common factor, and 3) three models where any two out of the three latent variables correlated fully while the correlation of the third one was allowed to vary freely, which results in two factor models. These results indicate that these three core components of executive functions are separable but intercorrelated processes.

1.4.2 The development of executive functions

Executive functions develop rapidly in early childhood. Before the age of three, EF components are emerging and great improvements can be seen in EF tasks between the age of three to five (Anderson, 2002; Diamond 2002; Garon et al., 2008). Nevertheless, improvements continue on throughout childhood and adolescence and even into adulthood (Anderson, 2002, Diamond, 2002; Garon et al., 2008). These improvements are not necessarily linear but may occur in developmental spurts (Anderson, 2002). In early childhood, the development of EF constitutes gaining certain abilities while development later in childhood and adolescence is more oriented towards fine-tuning abilities that have already emerged (Anderson, 2002; Best et al., 2011; Garon et al., 2008). The development of EF has been linked to the neuropsychological development of the prefrontal cortex (PFC) which is responsible for regulating thoughts and behavior by inhibiting or exciting other brain areas (Best & Miller, 2010; Diamond, 2002; Garon et al., 2008). The PFC has one of the slowest developmental trajectories of any brain region, and is not fully mature until in early adulthood (Anderson, 2002; Best & Miller, 2010, Diamond, 2002; Garon et al., 2008; Lee et al., 2013; Sander et al., 2012; Stuss & Alexander, 2000). The maturation of the PFC consists of both qualitative change in the structure and organization of the cortex, resulting in new abilities emerging, and quantitative change where activity is increased or streamlined, resulting in higher efficiency and accuracy (Best & Miller, 2010; Diamond, 2002).

Even though Miyake and colleagues' (2000) three factor model of EF has been relatively well established for the structure of executive functions in adults, there is still ongoing debate about the structure of EF in children. While some researchers find evidence of a three-factor structure in school aged children (Lehto et al., 2003; Rose et al., 2011; Wu et al., 2011), and even

children as young as five years old (Monette et al., 2011), others claim that EFs develop from a unitary structure in early childhood (Hughes et al., 2009; Miller et al., 2012; Wiebe et al., 2008; Willoughby et al., 2010) which differentiates into two structures by middle childhood (Huizinga et al., 2006; Lee et al., 2013; Stankov, 1978), and stabilizes as a three factor structure by adolescence (Fitzgerald et al., 1973; Lee et al., 2013). In a longitudinal study with a cohort sequential design, Lee et al. (2013) investigated changes in the factor structure of EF in children aged six to fifteen. Children aged six to ten showed a clear two factor structure, but by age eleven the factors began to differentiate further. By age 15 a well separated three-factor structure had been established.

Although the debate about the dimensionality of EF is still ongoing, researchers agree that developmental trajectories of different EF components differ substantially. Below is an overview of the development of each core component, as well as planning, which is a higher-order EF ability that involves all three core components to some extent.

1.4.2.1 Inhibition

The first indicator of inhibition emerges in infancy and develops substantially between six and twelve months of age (Anderson, 2002; Diamond, 2002; Garon et al., 2008). For example, in the A-not-B task, an object is hidden in one of two hiding places directly in front of the infant, one on the left and the other one on the right side from midline. Once the object has been hidden and retrieved from one of those places, a prepotent response to reach to the same place has been established. When the object is then hidden in the other location, this prepotent response has to be inhibited to retrieve the object from the correct hiding place (see Diamond, 2002). Seven-month-old infants are able to retrieve the item from the correct place with a two second delay. This ability develops rapidly and by 12 months, infants solve this task with a delay up to 12 seconds (Diamond, 1985). Another inhibition task that is possible to administer to infants is the object retrieval task (Diamond, 1990, 1991). An object is placed in a transparent box, where the opening faces away from the infant. Infants up to eight months old only reach for the object on the side that they are looking through and are thus unable to retrieve the object. Infants between ages 8.5 to 9 months are able to find the open side of the box but have to look through it while retrieving the object. Between 11 to 12 months, infants gain the ability to reach into the open side of the box while looking through the closed side in front of them.

Inhibition continues to develop rapidly for the first five years, which is consistent with a growth spurt in the PFC in the first years of life (Anderson, 2002; Diamond, 2002). By age three, children are able to inhibit prepotent responses reasonably well on simple inhibition tasks, such as standing completely still while researchers try to distract them (Klenberg et al., 2001), or stopping an enjoyable activity when told no by a caregiver (Kochanska & Aksan, 1995), although improvements continue up until age six even in these simplest tasks (Anderson, 2002; Davidson et al., 2006; Diamond & Taylor, 1996; Klenberg et al., 2001). Similarly, the urge to eat a treat can be delayed for 20 seconds by two-year-old toddlers, one minute by three-year olds, and five minutes by four-year olds (Carlson, 2005). Similar results have been found with computerized tasks, such as in tasks where the stimulus-response sets are on opposite sides (press left when stimulus is on the right; the Simon effect). Toddlers aged 2.5 years have accuracy rates slightly above chance levels and by age three, they are correct on 90% of trials (Geraldi-Caulton, 2000, see also Davidson et al., 2006). Between ages four and five, children become able to inhibit their responses on no-go trials in the go/no-go task (Diamond, 2002).

Young children are able to perform complex inhibition tasks, where a rule has to be kept in mind, a prepotent response inhibited, and another response produced, but accuracy rates rise substantially throughout the preschool years (Diamond, 2002; Diamond et al., 1997; Garon et al., 2008). Although adult-like performance can be reached early in development for the easiest tasks, for example at seven (Johnstone et al., 2007; Klenberg et al., 2001), ten (Pureza et al., 2013; Welsh et al., 1991) or eleven-years-old (Brocki & Bohlin, 2004; Huizinga & Van der Molen, 2007; Levin et al., 1991), many five and six year old children fail difficult tasks (Carlson, 2005; Garon et al., 2008). Improvements in speed can be seen throughout childhood and into adolescence (Diamond, 2002; Best & Miller, 2010; Huizinga et al., 2006), and even adulthood (Diamond, 2002; Best & Miller, 2010; Huizinga et al., 2006).

1.4.2.2 Working memory

The ability to hold representations in mind over a delay emerges in infancy and may even appear before six months of age (Garon et al., 2008; Johnson, 2005). With increased age, the length of time that representations can be retained increases (Gathercole, 1998), as well as the number of representations that can be held in mind simultaneously (Pelphrey & Reznick, 2002; Garon et al., 2008). For instance, by twelve months, infants can retrieve objects hidden in one of four possible locations (Pelphrey et al. 2004), and by

eleven years, children can retain up to fourteen items in a word span task (Gathercole, 1998).

The ability to manipulate information in working memory emerges at around two years old (Gathercole, 1998) and continues to improve into adolescence, where for example backwards digit span increases by a factor of five between ages six and thirteen (Dempster, 1981). There seems to be a linear increase in working memory capacity from early childhood into adolescence (Gathercole et al., 2004; Huizinga et al., 2006; Huizinga & Van der Molen, 2011; Lee et al., 2013) and even adulthood (Brocki & Bohlin, 2004; Huizinga & Van der Molen, 2007; Lee et al., 2013; Luciana & Nelson, 1998). Task difficulty affects performance on working memory tasks. In the simplest tasks, ceiling effects are found as early as in ten-year-old children (Pureza et al., 2013; Tsubomi & Watanabe, 2017) or even younger. Luciana and Nelson (1998) varied the number of possible locations in a search task and found that in the easiest condition, where there were only two possible locations, four-year-old children performed at adult-levels. When the number of locations was raised to three, ceiling effects appeared by age six and in the most difficult condition, where there were eight possible target locations, performance improved up until adulthood. Similarly, in a more recent study, Luciana et al. (2005) administered a variety of working memory tasks to children and young adults aged nine to 20. The tasks varied in complexity and they found that in the simplest task, no developmental differences were found, but in the more difficult tasks, performance improved linearly between ages nine and 16. These studies showed how task difficulty influences results and emphasizes the importance of finding the correct experimental design to reveal developmental differences.

To conclude, working memory capacity increases linearly from early childhood up until adolescence, and improvements can be found up until adulthood on the most complex tasks.

1.4.2.3 Attentional flexibility

Attentional flexibility is considered to involve both inhibition and working memory, because in order to be able to switch between two different mental sets, it is necessary to have the ability to keep them both in mind and inhibit the ongoing set before the other one is activated (see e.g. Anderson, 2002; Best & Miller, 2010; Garon et al., 2008). Perseverance is common in infancy but by the end of the first year of life infants are able to switch between two response sets, given that they get enough tries in the post-switch phase (Overman et al., 1996). This ability develops substantially between one and three years (Overman et al., 1996), although children still make perseverative

errors to some extent in the preschool years (Garon et al., 2008). Perseverance reduces gradually through childhood and has all but disappeared by adolescence (Anderson, 2002).

By age three or four, children are able to rapidly switch between two simple response sets but are unable to follow more complex rules (see e.g. Anderson, 2002; Best & Miller, 2010). Dimensional card sorting tests (DCST) are commonly used to measure flexibility. Observers are given a deck of cards and are asked to sort them according to a certain dimension, for instance color. After a while, the rules change and now the shape of the item on the card controls the sorting. Therefore, the blue plus sign that would have gone in the blue circle deck before the rule switch will now go into the yellow plus sign deck (see figure 8). When testing young children, the decks are normally simpler, with two possible rules and two decks to choose from. By age four, most children are able make a single switch in this simplified version of the task (Diamond, 2002; Zelazo et al., 1995, 1996).

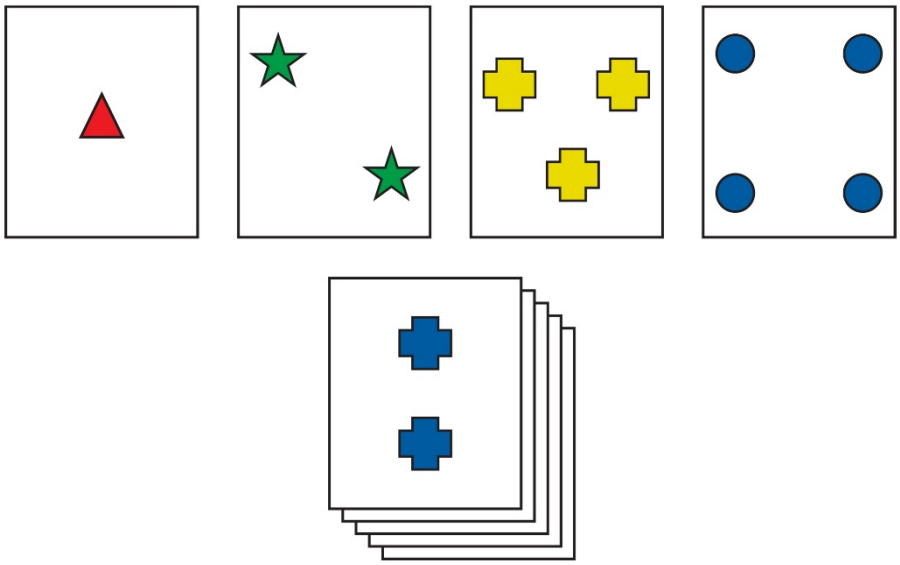

Figure 8. The Wisconsin Card Sorting Test (WCST). The cards can be sorted by three dimensions, color, shape, and number. It depends on the current rule whether the example card will go into the deck with the two green stars, three yellow plus signs, or four blue circles. Image reproduced from researchgate.net. Image credit: Derek Evan Nee.

Improvements in task switching abilities develop throughout childhood and into adulthood. When task switching dimensions increase beyond two, even seven-year-old children struggle with the task (Anderson et al., 2000; Huizinga & Van der Molen, 2011). Although performance improves substantially in the next years (Anderson et al., 2000), eleven-year-old children have not yet reached adult levels of accuracy (Cohen et al., 2001).

Another way to measure attentional flexibility is with switch-costs, which are the increases in time it takes to respond during switches compared to non-switches. Young children do not necessarily exhibit large switch costs, they tend to persevere and make errors rather than slow down in an attempt to make an accurate response (Cohen et al., 2001; Davidson et al., 2006). By age seven, children exhibit large switch costs which decrease linearly into adulthood (Cepeda et al., 2001; Kray et al., 2004), although some studies have found adult like performance in adolescents (Huizinga et al., 2006) or even eleven-to-twelve-year-old children (Anderson, 2002; Huizinga & Van der Molen, 2007; Pureza et al., 2013). To summarize, attentional flexibility emerges later than inhibition and working memory as it is dependent upon the other two processes. Young children tend to persevere on task switching tasks, but accuracy increases throughout childhood. By age seven, it is possible to measure switch costs, which decrease into adulthood.

1.4.2.4 Planning

A number of researchers posit that the three core components of EF combine in different ways to form complex, higher-order EFs, such as planning, organizing and goal-directed behavior (e.g. Clark et al., 2010; Kroesbergen et al., 2009). Planning has been described as the pinnacle of executive functioning (see Best et al., 2009) and involves the ability to strategize and organize behavior in advance so that tasks can be resolved efficiently (Anderson, 2002; Best et al., 2009). Planning involves all three core components: Inhibition is required to stop and think before one acts, working memory is necessary to formulate a plan and keep it in mind, and attentional flexibility is essential for evaluating the current course of action and change behavior if the current behavior is not helpful towards reaching a certain goal.

Young children struggle with planning and organizing their behavior. By the age of four, children have developed rudimentary planning abilities (Welsh et al., 1991; Luciana & Nelson, 1998). Planning abilities are often studied with the Tower of London (ToL) or Tower of Hanoi (ToH) tasks. In the ToL task, observers have to move differently colored beads between pegs and try to copy the setup of the pegs of the examiner‘s board (see figure 9). Only one

bead can be moved at a time and the lengt of the pegs dictates how many beads they can hold. The ToH task is based upon a similar principle. The pegs are all of the same length, but the beads are of different sizes, and larger beads cannot be put on top of smaller beads. The number of moves and timing of task completion are documented.

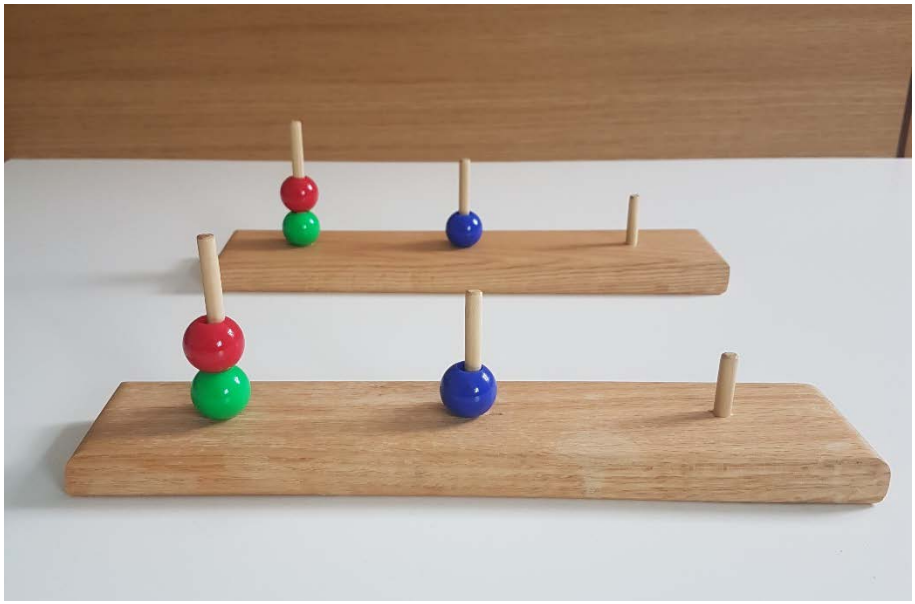

Figure 9. The Tower of London task. The examiner arranges the beads on his or her board and the observer is asked to copy the arrangement of the examiners board, in as few moves as possible.

Luiciana and Nelson (1998) studied children‘s planning abilities with the ToL task. In the easiest condition, where only two moves were needed to complete the task, there was no difference between the performance of four-year olds and older children and adults. When one more move was necessary to complete the task, four-year-old children performed worse than eight year olds and adults, and when even more moves were needed to complete the task, both four and eight year old children performed worse than adults. Planning abilities develop rapidly in middle childhood and gradual improvements can be seen into adolescence (Krikorian & Bartok, 1998) and adulthood (Huizinga et al., 2006).

1.4.2.5 The development of executive functions: Summary

The core components of executive functions all have slightly different developmental trajectories. Inhibition and working memory emerge in the first year of life and inhibition develops rapidly in the preschool years. Small improvements in computerized inhibition tasks can be seen into adolescence and even adulthood. The development of working memory is more gradual: The ability to manipulate information retained in memory emerges around two years of age, and linear improvements are seen into adolescence, and sometimes adulthood. Attentional flexibility involves both inhibiton and working memory and therefore emerges later in life. Perseverance behavior declines rapidly between ages one and three, and rudimentary task switching abilities are seen by age three or four. Just as for working memory, attentional flexibility develops linearly throughout childhood and adolescence. Rudimentary planning capability is established by four years of age and develops until adulthood.

Planning and other higher-order EFs involve the three core components, and some evidence points towards differential relations between core components and complex EFs throughout development. Senn et al. (2004) studied inhibition, working memory, attentional flexibility, and planning abilities in children aged two to six. They found that in children younger than four years old, inhibition was the best predictor for performance on the ToL planning task, but for children over the age of four, working memory, but not inhibiton, predicted planning performance. Similarly, Huizinga and Van der Molen (2007) found that performance in the Wisconsin Card Sorting Test was predicted by inhibition and attentional flexibility in seven-year-old children, attentional flexibility in 11-year-old children, both attentional flexibility and working memory in 15-year-olds, but only working memory in adults. Inhibition develops rapidly in early childhood and young children seem to rely heavily on their inhibitional abilities to navigate difficult tasks. As working memory and attentional flexibility develop, more emphasis is put on those abilities for problem solving and goal-oriented behavior.

1.5 Visual attention and executive functions

As mentioned above, many researchers have suggested that poor executive functions can explain children's inefficiency in conjunction search tasks, especially inhibition (Hommel et al., 2004; Jenkins & Berthier, 2014; Longstaffe et al., 2014; Merrill & Lookadoo, 2004; Sander et al., 2012) and working memory capacity (Anderson et al., 2010; Cowan et al., 2006; Donnelly et al., 2007; Longstaffe et al., 2014, but see Jenkins & Berthier, 2014 and Kane et

al., 2006, for contradictory results). Anderson et al. (2010) investigated the relationship between working memory and visual search in a functional magnetic resonance imaging (fMRI) study. They found that the same cortical areas are activated during serial visual search and both object-based and spatial visual working memory tasks. Moreover, they found dual-task inference when either of the two working memory tasks was administered alongside visual search, indicating a competition for the same cortical resources to complete the tasks. They propose that the inferior and middle frontal cortex in the right hemisphere are responsible for both working memory and difficult visual search.

Gil-Gómez de Liaño et al. (2020) compared the normalized developmental trajectories of their measures of visual search performance with the normalized developmental trajectories of various executive functions outlined by Anderson (2002). They found that search accuracy had a similar trajectory to attentional control, while the intercept, which is believed to indicate information processing and motor response times, had a trajectory corresponding to information processing and cognitive flexibility in Anderson's study. Finally, the trajectory of the search slope corresponded to the trajectory of goal setting (see figure 10).

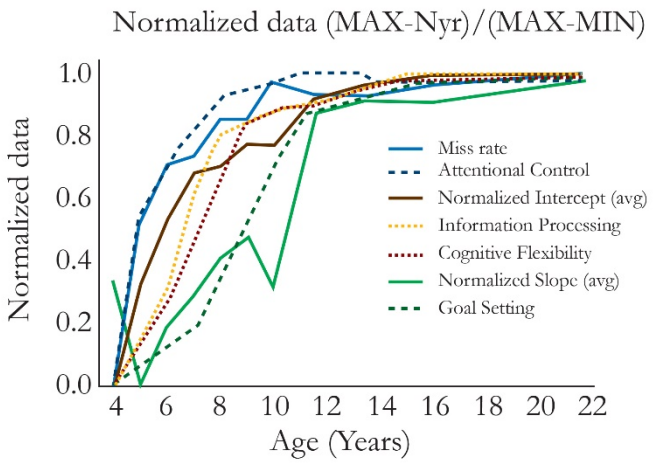

Figure 10. Comparison of performance in the unique search task from Gil-Gómez de Liaño and colleagues (2020) and executive functions from Anderson (2002). Search accuracy has a similar developmental trajectory as attentional control, the intercept as information processing and cognitive flexibility, and search slopes as goal setting. Image reproduced from Gil-Gómez de Liaño et al. (2020). License: http://creativecommons.org/licenses/by/4.0/

2 Aims

Given that foraging research with adult participants has revealed that single target search tasks do not necessarily tell us the whole truth about how the visual system works, it is important to also use foraging tasks to study how visual attention develops. Foraging tasks should provide deeper insights into attentional development than previously possible, they are dynamic and generate multifaceted datasets where multiple aspects of attentional orienting over time can be studied.

There were two overarching aims of this project: The first aim was to gain deeper insights into the development of visual attention throughout childhood. The second aim was to link developmental differences in visual attention to the development of executive functions. Paper I and II revolve around the development of target switching and foraging speed, and whether these aspects of foraging are related to executive functions. In paper III, the development of foraging organization, or movement patterns through the display, were investigated.

2.1 Paper I: Visual foraging and executive functions: A developmental perspective

In the first study of this project, we compared the foraging of children aged four-to-seven, eleven-to-twelve, and young adults, to acquire a broad outline of foraging abilities and developmental changes from the preschool years up until adulthood. The focus of this study was on target switching, both the number of runs and switch costs, as well as ITTs throughout the trials. Previous studies on adults had shown that they switched between target types repeadedly during feature foraging, with no cost to ITTs, but when foraging for conjunctively defined targets, they tended to refrain from switching, often completing trials in two runs (e.g. Kristjánsson et al., 2014). A previous study on the foraging of young children found that unlike adults, they avoided switching between target types, even during feature foraging (Ólafsdóttir et al., 2016). We were therefore especially interested in finding out how older children foraged, and whether they had reached adult levels of performance by age eleven.

We also administered a battery of EF tasks to the older children and adults. These tasks tapped the three core components of EF: Inhibition, attentional

flexibility, and working memory, as we wanted to find out whether EF had any connection to performance in the foraging task, and especially whether there were any age differences in how these abilities were connected.

2.2 Paper II: Age differences in foraging and executive functions: A cross-sectional study

In paper II, we wanted to obtain more fine-grained knowledge of how foraging abilities develop throughout childhood and a deeper understanding of their connection with EF. We therefore tested more age groups than before, children from age six up to fifteen, as well as young adults. We also added a measure of problem solving or planning abilities, as well as using a measure of simple inhibition instead of the complex measure used in the previous study. Because of the youngest children's difficulty with completing the foraging task in the previous study, we simplified it by decreasing the number of items on the screen by 50% and did not test children that had not started formal schooling, raising the age of the youngest participants up to six years.

2.3 Paper III: The development of foraging organization

The final study of this project revolves around another aspect of visual attention. Foraging organization concerns how systematically children are able to move through the foraging display. We measured the foraging organization of children of various ages with various methods and compared their organizational abilities with those of young adults. Previous studies have shown that organizational abilities are connected to conjunction search in single target tasks (Woods et al., 2013), so we compared other measures of foraging, in both the feature and conjunction tasks, with organizational ability. Lastly, we investigated whether the diminished organization found in conjunction compared to feature foraging was due to a higher mental load demanded by the more difficult task, or whether it might be due to observers treating each conjunction foraging trial as two separate foraging paths, one for each target type.

3 Paper I

The following chapter is a manuscript published in Acta Psychologica under the name Visual attention and executive functions: A developmental perspective. The authors are Ólafsdóttir, I. M., Gestsdóttir, S. & Kristjánsson, Á. Figure numbers, references and some formatting has been changed from the published paper for continuity with the thesis as a whole. Any references to content within this chapter should be as follows:

Ólafsdóttir, I. M., Gestsdóttir, S., & Kristjánsson, Á. (2019). Visual foraging and executive functions: A developmental perspective. *Acta Psychologica*, *193*, 203-213.

3.1 Abstract

Visual foraging tasks, where participants search for multiple targets at a time, may provide a richer picture of visual attention than traditional single-target visual search tasks. To contribute to the mapping of foraging abilities throughout childhood and to assess whether foraging ability is dependent upon EF abilities, we compared the foraging of 66 children aged 4–7 years (mean age=5.68 years, SD=0.97 years, 33 girls), 67 children aged 11–12 years (mean age=11.80 years, SD=0.30 years; 36 girls), and 31 adults aged 20–37 (mean age 30.32 years, SD 4.37 years, 18 females) in Iceland, with a task involving multiple targets of different types. We also measured three subdomains of executive functions; inhibition, attentional flexibility, and working memory. Our results show that foraging improves dramatically between the preschool and middle school years, with the older children showing similar foraging abilities as adults due to greater ease of switching between target types. The older children and adults randomly switch between target templates during feature foraging, but exhaustively forage for a single target type before switching during conjunction foraging. Younger children, conversely, tended to also stick to the same target type for long runs during feature foraging, showing that they have difficulties with feature-based tasks. Switch costs were much lower for the older children than the youngest age group, and on par with those of adults, resulting in fast and efficient foraging. Lastly, we found a connection between foraging ability and both working memory and attentional flexibility, but not inhibition. Our study shows that foraging is a promising way of studying visual attention, how it changes throughout the lifespan, and how it is connected to other cognitive functions.

3.2 Introduction

Traditionally, human visual attention has been studied with search tasks, where participants look for a single target among numerous distractors (Bravo & Nakayama, 1992; Kristjánsson, 2015; Treisman & Gelade, 1980; Wolfe, 1994). Recently, visual foraging, where participants look for many targets on the same trial, has received increased interest (Cain et al., 2012; Kristjánsson et al., 2014; Wolfe, 2013). This paradigm originally comes from studies on animals (Bukovinszky et al., 2017; Dawkins, 1971; Mallott et al., 2017; Pyke et al., 1977, Schuppli et al., 2016), and may better capture orienting in the visual environment than single target searches, where a target is to be found, and the search then ends. One typical finding is that when food items are abundant and easily found, animals forage for multiple food types at the same time, but when they are difficult to find, they tend to forage in runs; that is, select only one type of food for an extended period of time (Bond, 1983; Dukas, 2002). This behavioral shift has been attributed to limited attentional capacities; when food is difficult to find, attentional load is high, and then the optimal strategy is to limit foraging to one food type. When the targets are easy to find, there is little effort in simultaneously foraging for different types of food and gathering more items in less time (Dukas, 2002). Studies with computerized foraging tasks have shown that human foraging behavior resembles that of animals, where they adapt their search strategy to the distribution of target items in the environment to optimize hit rate (Bond, 1982; Cain et al., 2012; Kristjánsson et al., 2014).

A foraging task developed for iPads by Kristjánsson et al. (2014; see also Jóhannesson et al., 2016; Kristjánsson et al., 2016, Á. Kristjánsson et al., 2018; T. Kristjánsson et al., 2018), has been used to gain insight into how humans forage for targets from different target categories. The original display consists of multiple items from four different categories, two of which are targets and two distractors. Participants are instructed to tap all targets as fast as they can, while avoiding distractors. One of the main dependent variables in this paradigm is the foraging pattern, measured in the number of runs, where a run is defined as the repeated selection of the same target type. The number of runs is inversely related to run length and is essentially a measure of how often participants switch between target types. When switches are frequent, the trial will consist of many short runs. When participants repeatedly select the same target type, the trial will consist of a few long runs. To manipulate attentional load, the foraging task can be either feature or conjunction based (Kristjánsson et al., 2014). During feature foraging, the targets are defined by only one

feature; color. Participants are instructed to tap all the disks of two colors but avoid tapping the distractor items. In this condition, adult participants frequently and effortlessly switch between target categories. Task difficulty increases in the conjunction condition,where the items are defined by two features; color and shape. Now attentional load is higher, and participants tend to change their foraging pattern by selecting targets of the same type in long runs, most frequently tapping every single target of one category before switching to the next (Jóhannesson et al., 2016, 2017; Kristjánsson et al., 2014).

To our knowledge only one study has examined foraging and executive functions. Jóhannesson et al. (2017) considered the relationship between foraging and the cognitive capabilities of adults (M_{age}=25 years). Participants were divided into two groups based on the number of runs during conjunction foraging and their performance on working memory and inhibition tasks measured. No connection was found between foraging patterns and executive functions (EF). While most studies using this paradigm have focused on the number of runs, other measures, such as foraging speed and switch costs, can also provide insight into foraging abilities and visual attention. We therefore make a distinction between foraging patterns, measured in the number of runs, and overall foraging ability, which can be measured in various ways as listed above, including foraging patterns. In Jóhannesson et al. (2017), neither foraging speed nor other indicators of foraging abilities were compared to EF performance, and it is unknown whether they are connected to other aspects of foraging, and to what extent foraging relies on cognitive capacities. Our aim was to assess different aspects of foraging abilities by measuring foraging patterns, speed, and switch costs of both children and adults, comparing them with their performance of three EF subcomponents; inhibition, attentional flexibility, and working memory.

3.2.1 Foraging from a developmental perspective

Little is known about the foraging abilities of children and how they develop into adulthood. Considering the insights into visual cognitive processes gained from foraging studies, such studies may provide valuable information on the development of visual attention. Single target visual search tasks have revealed that feature search abilities mature at a very young age (Gerhardstein & Rovee-Collier, 2002), and may even be in place in infancy (Adler & Orprecio, 2006), while processing of conjunctively defined targets is still developing during middle childhood, reaching a peak in young adulthood (Donnelly et al., 2007; Merrill & Conners, 2013; Merrill & Lookadoo, 2004; Taylor et al., 2003; Trick & Enns, 1998; Woods et al., 2013).

Children's difficulty with conjunction search has partly been attributed to underdeveloped executive functioning (Donnelly et al., 2007; Trick & Enns, 1998; Woods et al., 2013), which is a complex network of cognitive processes that underlie action planning and goal directed behaviors. Fundamental subcomponents of EF include working memory, attentional flexibility, and inhibition (Best & Miller, 2010; Hommel et al., 2004; Miyake et al., 2000). EF is at least partly dependent on the development of the prefrontal cortex, which does not reach full maturity until young adulthood, usually around age 25 (e.g. Conklin et al., 2007; Diamond, 2002; Diamond & Goldman-Rakic, 1989; Moriguchi & Hiraki, 2009).

Although inhibitional abilities improve rapidly over the preschool years (Klenberg et al., 2001), they continue to develop at a slower rate into middle childhood (Brocki & Bohlin, 2004; Romine & Reynolds, 2005). A few studies using computerized tasks have found that speed and accuracy in inhibitional tasks improve somewhat during adolescence (Leon-Carrion et al., 2004), and even early adulthood (Huizinga et al., 2006). These improvements during adolescence and early adulthood (age range 18–29) seem to represent greater ease with inhibiting prepotent responses, while the acquisition of inhibition during preschool years involves fundamental changes in cognition, such as a newfound ability to form rules (Best & Miller, 2010; Best et al., 2009).

Attentional flexibility and working memory develop later than inhibition and continue to improve throughout adolescence (Davidson et al., 2006; Lee et al., 2013). Attentional flexibility is believed to rely on inhibition because it involves inhibiting previous activities and switching to other tasks (Best et al., 2009), and has been shown to develop at a slower rate than inhibition, with children not yet performing at adult levels by age 13 (Davidson et al., 2006). Younger children's difficulty with task switching is reflected in perseverance, or a failure to change behavior according to task demands (Anderson, 2002). As children become older, perseverance errors diminish greatly. Instead of measuring error rates, attentional flexibility can then be measured with switch costs, which involve the difference in response times between switch and no-switch trials (Huizinga et al., 2006).

Many studies have shown that working memory performance improves linearly from early childhood and throughout adolescence (Conklin et al., 2007; Gathercole et al., 2004; Hale et al., 1997). When task demands are low, such as when asked to hold two items in mind, preschool aged children perform working memory tasks at adult levels. As soon as the tasks become more complex and memory load increases, their disadvantages become apparent

(Luciana et al., 2005). Performance on many working memory tasks stabilizes between ages 11 and 15 (Conklin et al., 2007; Luciana et al., 2005), and as early as 9–10 years on recognition memory tasks (Luciana et al., 2005), but for the most complex tasks, improvements are seen until age 17 (Conklin et al., 2007).

Mental planning and flexibility, working memory, and inhibition are believed to play a large role in conjunction search, guiding spatial attention and preventing return to searched locations (Woods et al., 2013). Additionally, inhibitory control is believed to contribute to increased efficiency in conjunction search with development, by inhibiting distractors, which is arguably harder in conjunction than feature search (Hommel et al., 2004). The limitations of young children's xecutive processing ability can thus hamper their conjunction search performance. These limitations do not affect feature search performance, which is relies on simpler processing mechanisms (Woods et al., 2013). Ólafsdóttir et al. (2016) investigated the foraging abilities of 4-7-year-old children, connecting their performance with self-regulation and working memory measures. They found that the foraging patterns (measured with the number of runs) of young children differ from those of adults (M_{age}=28.3 years). The children foraged in long runs, not only during conjunction foraging, but also during feature foraging. No connection was found between foraging patterns and self-regulation and working memory, although both constructs were related to faster foraging and a higher number of completed trials during conjunction foraging. Hence, EF may affect some aspects of foraging, but more research is needed to determine the nature of this relation.

3.2.2 The current study

We had two main objectives; to continue the mapping of foraging abilities throughout childhood and to estimate whether foraging ability is dependent upon EF abilities. We compared the foraging and EF abilities of three age groups; young children aged 4–7 years, older children aged 11–12 years, and adults. We administered the foraging task developed by Kristjánsson et al. (2014), measuring foraging patterns, foraging speed, and switch costs, along with three EF tasks from the Amsterdam Neuropsychological Tasks program (ANT; de Sonneville, 1999); inhibition, attentional flexibility, and working memory.

By the age of 11 years, EF abilities have developed substantially, although they have not quite reached adult levels (Best et al., 2009; Best & Miller, 2010; Davidson et al., 2006; Lee et al., 2013). We therefore predicted that foraging patterns of 11–12-year-old children would be close to those seen for adults,

with the distribution of the number of runs during feature foraging close to random, but with most trials during conjunction foraging limited to two runs (Jóhannesson et al., 2016, 2017; Kristjánsson et al., 2014; Á. Kristjánsson et al., 2018; T. Kristjánsson et al., 2018). This pattern should differ from that of 4–7-year-old children who tend to also forage in long runs during feature trials (Ólafsdóttir et al., 2016). Given the developmental differences in both EF's and overall cognitive speed due to the development of general information processing (Hommel et al., 2004; Kail, 1991), we also predicted that these older children would forage significantly more quickly and efficiently than the younger children, but at a slower rate, and with higher switch costs, than adults.

Additionally, we expected a connection between foraging and all measures of EF. High working memory capacity should make it easier for participants to keep both target categories in mind (Awh & Jonides, 2001; Bundesen, 1990), diminishing both hesitations during trials and lowering switch costs, and therefore overall foraging speed. Greater attentional flexibility should both lower switch cost and facilitate switching between target categories (Huizinga et al., 2006) resulting in more runs. Finally, we believed that greater inhibitional abilities should facilitate switching between target categories by inhibiting prepotent responses; in single target search, participants seem to prefer targets of the same type as they have been attending before, and inhibition should be needed to counter that preference, again resulting in more runs (Brascamp et al., 2011; Chetverikov & Kristjánsson, 2015). High levels of executive functioning should therefore result in more runs per trial and lower switch costs, as well as faster and more efficient foraging.

3.3 Method

3.3.1 Participants

Three age groups were compared. The youngest age group consisted of 42 kindergarteners and 24 first graders, aged from 4.08 to 7.17 years (mean age=5.68 years, SD=0.97 years, 33 girls, previously collected data from Ólafsdóttir et al., 2016). In the second age group there were 67 sixth grade students from an elementary school in Reykjavik. Their age ranged from 11.22 to 12.24 years (mean age=11.80 years, SD=0.30 years; 36 girls). Lastly, there were 31 adult participants aged 20–37 (mean age 30.32 years, SD=4.37 years, 18 females). The kindergarten and school-aged participants were all recruited from the same school district. All participants had normal or corrected to normal vision. Approval from school administration was obtained, in addition to verbal consent from each participant and parental consent for underaged participants.

All aspects of the experiment were reviewed and approved by the data protection authority and permission was granted by the Reykjavik Department of Education and Youth.

3.3.2 Equipment

The foraging task was presented on an iPad 2 with screen dimensions of 20×15 cm and an effective resolution of 1024×768 pixels, placed on a table in front of participants in landscape mode, so that viewing distance was approximately 50 cm. Stimulus presentation and response collection were carried out with a custom iPad application written in Swift using Xcode. The EF tasks were administered on a 17.3″ laptop computer screen with an effective resolution of 1600×900 pixels. Task presentation and response collection were carried out with the ANT program (de Sonneville, 1999).

3.3.3 Stimuli

At the start of each trial of the foraging task, there were 80 stimuli on the screen, half were targets and the other half distractors. During feature foraging the stimuli were green, red, yellow, and blue disks. For half the participants, the red and green disks were targets and the yellow and blue disks distractors, and for the other half this was reversed. During conjunction foraging the stimuli were red and green disks and squares. For half the participants, the targets were red disks and green squares, and the distractors were green disks and red squares, but for the other half this was reversed. The diameter was 20 pixels (approximately 0.46° visual angle). The items were randomly distributed on a non-visible 10×8 grid and offset from the screen edge by 100×150 pixels. The viewing area therefore occupied 12×15 cm (approximately 13.7×17.1°). The position of individual items within the grid was jittered by adding a random vertical and horizontal offset while gaps between columns and rows ensured that items never approached or occluded one another. The location of target and distractors, and therefore the overall spatial layout, was randomly generated from trial to trial (see Fig. 11).

Two tasks from the ANT program were used to assess executive functions. The Response organization – objects (ROO) was used to assess inhibition and attentional flexibility. The second part of Memory search 2D stimuli (MS2D) was used to assess working memory.

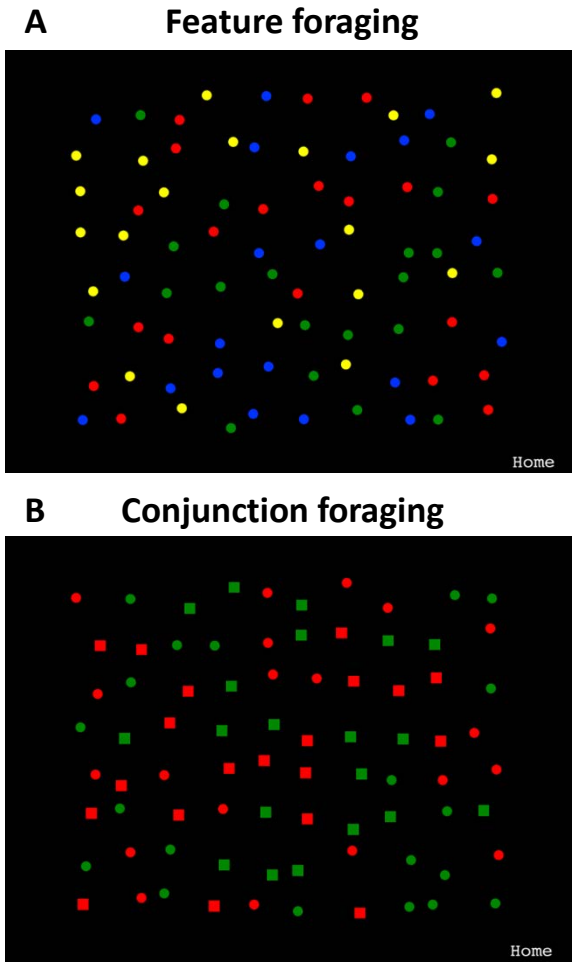

Figure 11. Examples of the iPad foraging tasks. **Panel A** shows the feature condition, where the task is to tap all red and green disks while ignoring the blue and yellow ones (or vice versa). **Panel B** shows the conjunction condition where the task is to tap all the red disks and green squares (or vice versa). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In ROO the stimulus is a disk that appears on the left or right-hand side of a fixation cross. In the first part, the disk is always green, in the second part always red, and in the third and final part the disk can be either red or green. In all parts, the disk location is pseudorandom, as is the disk color in the third part.

In MS2D the participant is asked to look at, and memorize, three shapes and their color; a blue triangle, a green square, and a yellow cross. On each trial, the stimuli are four shapes presented on the corners of a virtual square. The shapes are a circle, a square, a triangle, and a cross. There is always one shape of each color; red, green, blue, and yellow. Their color and location are presented in pseudorandom order, and a target is present on half of the trials.

3.3.4 Procedure

The experiment was run in a quiet room with normal illumination. Each kindergarten and school aged participant finished two 15-minute sessions on different days, with a maximum of one week between them. They completed the foraging task in one session and the EF tasks in the other. The adult participants completed all tasks in one session. The order of the foraging and EF tasks was counterbalanced, so that half of the participants started with the foraging task, and the other half with the ANT tests. During each session, the task order was also counterbalanced. In the foraging session, half of the participants started with feature foraging and the other half with conjunction foraging. The colors of the targets were also counterbalanced. In the ANT session, the order of the EF tasks was counterbalanced so that half of the participants started with the ROO and the other half with the MS2D.

3.3.4.1 Foraging

In the foraging task, the participants were asked to tap all targets as quickly and accurately as they could with the index finger of their dominant hand but avoid tapping the distractors. They were informed that the first trial of each foraging condition was a practice trial, and the remaining nine trials constituted the task itself. Each trial was started by pressing an on-screen play button. The targets disappeared upon being tapped. When participants had tapped all targets, a smiley face appeared along with information about how long it had taken to tap all 40 targets. If a distractor was accidentally tapped, the trial ended, and a frowny face appeared on the screen. The 11–12-year-old and adult participants were asked to fully complete ten error free feature foraging trials and ten error free conjunction foraging trials. The 4–7-year-old participants were asked to complete five error free trials of each foraging condition. The participants were told that they could take a break between any two trials. A counter in the bottom-left corner of the screen indicated the number of completed trials, and the researcher told participants when they performed the last trial of each condition.

3.3.4.2 Response organization

The ROO task consisted of three parts. In the first part, a green disk appeared on either the left or right-hand side of a fixation cross, and participants were asked to press the left key if it was on the left-hand side of the cross and the right key if on the right. In the second part, the disk was always red, and participants were asked to press the key opposite to where the disk appears, so if it was on the left side they should press the right key, and vice versa, (inhibiting a prepotent response). In the third part, the disk could be either red or green. If the disk was green, participants should press the key on the same side as the disk appears. If it was red, they should press the key on the opposite side. This part assessed attentional flexibility, since participants must switch between response sets. Participants were asked to keep their index fingers on the response keys throughout each trial and respond as quickly and accurately as possible. The disk remained on the screen until participants pressed a response button, or for a maximum of 7000 ms if no response was made. Responses were valid if they occurred between 200 and 6000 ms after stimulus appearance. The time between response and stimulus appearance was fixed at 1200 ms. If participants missed a trial, a trial was added at the end of the session so that the response number was the same for all participants. Before each part, participants were shown how the stimuli appeared on the screen, given instructions on how to respond and performed eight practice trials before the task itself started. Parts one and two consisted of thirty trials each and part three of sixty trials, thirty for each color.

3.3.4.3 Memory search

In the MS2D task, participants saw three shapes and were asked to memorize them and their color. They were then informed that each trial consisted of four shapes, presented on the corners of a virtual square. If one of the shapes was a memorized shape, participants were asked to press the yes-key, while if not they should press the no-key. Participants were asked to keep their index finger on the response keys throughout the session and respond as quickly and accurately as possible. The response key was always on the same side as the participants dominant hand. The shapes remained onscreen for 7000 ms or until response. A mask subsequently appeared until the next trial started after 1200 ms. Responses were valid if they occurred between 200 and 6000 ms after the stimuli appeared. Each session started with 12 practice trials, after which participants were asked if they still remembered the shapes and were then shown the memory set again if they were unsure of the target items. The session lasted 48 trials but if a participant missed a trial, the same shapes

reappeared but at different locations, so the number of responses for every participant was held constant.

3.3.5 Dependent variables and data analysis

The first trial of both foraging conditions was considered a practice trial and erased from further analysis. Taps on the areas between targets were also excluded from analysis, as well as the errors and the first tap of each trial. Results from error trials was analyzed like other trials, up to the point a distractor was tapped, and the trial ended, excluding the analyses on the number of runs. Since not completing a trial would result in fewer runs and skew the results, the number of runs was only calculated based on fully completed trials. Foraging speed was measured in inter-target times (ITTs, the time between taps on two targets). Other dependent variables were switch costs and the number of runs. A run is defined as repeated selection of the same target category. The number of runs is inversely proportional to run length; the longer the runs in each trial, the fewer they will be. Since each trial consists of 40 targets divided into two categories, the minimum run number on each trial is two (participants exhaustively forage for one target category before turning to the other). The maximum run number is 40 (participants switch between target categories after each tap on a target). In the former case, the length of the two runs is 20, 1 in the latter.

The mean run number and mean ITTs were calculated for each participant in each foraging condition and used to compare foraging with EF measurements. Additionally, switch costs in both foraging conditions were calculated for each participant by subtracting the mean ITTs of every tap in a run except from the first one from the mean ITTs of the first tap in a run, where the participant switches from the other target category. Note that during conjunction foraging the switch rate is much lower than during feature foraging, so any between-condition comparison of switch costs must carry this caveat.

In line with previous research using the ANT (see e.g. Brunnekreef et al., 2007; Mesotten et al., 2012; Schuitema et al., 2013), two new variables were created by subtracting the RTs from the first part of ROO from the RTs from the second and third parts for each participant, to obtain measures of inhibition and attentional flexibility, respectively. By subtracting the RTs of the task measuring baseline response speed from the RTs of the tasks measuring inhibition and attentional flexibility, we get a purer measure of those effects since we do not measure overall differences in response speed between participants, but only how the added tasks of inhibiting prepotent responses and switching of task demands affects RTs.

The dependent variable in the working memory task was the mean RT for hits (i.e. correctly identified targets). A multiple regression analysis run in blocks was used to assess the relationship between foraging and executive functions. Repeated measures ANOVAs were run to assess differences between foraging conditions. Analyses were performed with SPSS.

3.4 Results

Table 1 shows descriptive statistics for performance on the foraging task. The differences in error rates, runs, and foraging speed reveal that conjunction foraging condition is far more difficult than feature foraging for all age groups. Participants are slower, more prone to error, and refrain from switching between target categories during conjunction foraging. Foraging also improves with age. ITTs decrease with age (feature foraging: $F(2, 158)=61.18$, $p < 0.001$, $\eta_p^2 = 0.438$, conjunction foraging: $F(2,148) = 84.24$, $p < 0.001$, $\eta_p^2 = 0.532$), the number of runs during feature foraging increases slightly ($F(2, 158) = 4.37$, $p = 0.014$, $\eta_p^2 = 0.052$, for conjunction foraging, $p=0.380$, $\eta_p^2 = 0.013$), and error rates decrease. Note that the youngest participants (from Ólafsdóttir et al.,

Table 1. Foraging speed, the number of runs, and error rates, during feature and conjunction foraging.

	Feature foraging		Conjunction foraging	
	Mean	Sd	Mean	Sd
4-7-year-old				
ITTs (ms)	1143.30	653.04	1287.70**	588.64
Number of runs	10.94	8.23	4.98**	5.39
Errors	2,06	1.96	2.78	2.93
Errors per trial	0.79	1.04	1.46**	1.42
11-12-year-old				
ITTs (ms)	434.97	64.85	525.53**	88.51
Number of runs	13.38	2.85	4.56**	2.53
Errors	1.52	1.78	2.28*	2.21
Errors per trial	0.17	0.20	0.25*	0.25
Adult				
ITTs (ms)	348.34	50.25	451.44**	85.20
Number of runs	14.25	4.70	3.80**	2.12
Errors	0.58	0.85	1.45*	1.39
Errors per trial	0.06	0.09	0.16*	0.15

* The differences between feature and conjunction foraging within age-groups were statistically significant at 0.01 (paired samples *t*-tests).

** The differences between feature and conjunction foraging within age groups were statistically significant at 0.001 (paired samples *t*-tests).

2016) only had to complete four trials per condition, but the older participants were asked to complete nine trials. Many of the youngest participants were not able to complete all trials, so the number of trials per participant varied from one to four during feature foraging and zero to four during conjunction foraging. The mean number of errors per trial was calculated as well as the mean number of errors per participant, to enable comparison of error rates across age groups. Two 2×3 ANOVAs on errors and age group show that error rates decrease as participants get older during both feature, $F(2, 158)=18.79$, $p < 0.001$, $\eta_p^2 = 0.192$, and conjunction foraging, $F(2, 147) = 35.45$, $p < 0.001$, $\eta_p^2 = 0.325$.

3.4.1 Foraging pattern

Fig. 12 shows the distribution of the number of runs of all three age groups by foraging condition. The foraging patterns of the 11–12-year olds are much more similar to those of adults than the young children. During feature foraging, there is a clear peak at two runs for the younger children, showing that mostly they tapped all targets of one category before moving on to the next; a strategy seen for the conjunction foraging condition in older participants, but rarely during feature foraging. The run distribution for both the 11–12-year-olds and adults is bell-shaped, peaking between 14 and 18 runs, indicating that switches between target categories are frequent and close to random. Note, however, that a small peak can be seen at two runs for the adults, which reflects the foraging patterns of three participants who completed most trials in only two runs. The remaining 28 adults completed most trials by randomly switching between target categories, resulting in more runs per trial. Conversely, during conjunction foraging, the number of runs was highly positively skewed in all age groups, peaking at two runs, indicating that most participants foraged exhaustively for one target category before switching to the other. A repeated measures ANOVA on run number for feature vs conjunction foraging was run with age as a between subject factor. There was a main effect of both foraging condition, $F(1, 123) = 354.88$, $p < 0.001$, $\eta_p^2 = 0.743$, and age group, $F(1, 123) = 19.76$, $p < 0.001$, $\eta_p^2 = 0.243$, and a significant interaction between age group and condition, $F(2, 123)=19.88$, $p < 0.001$, $\eta_p^2 = 0.244$. The interaction reflects that there are differences in the number of runs during feature but not conjunction foraging (Table 1).

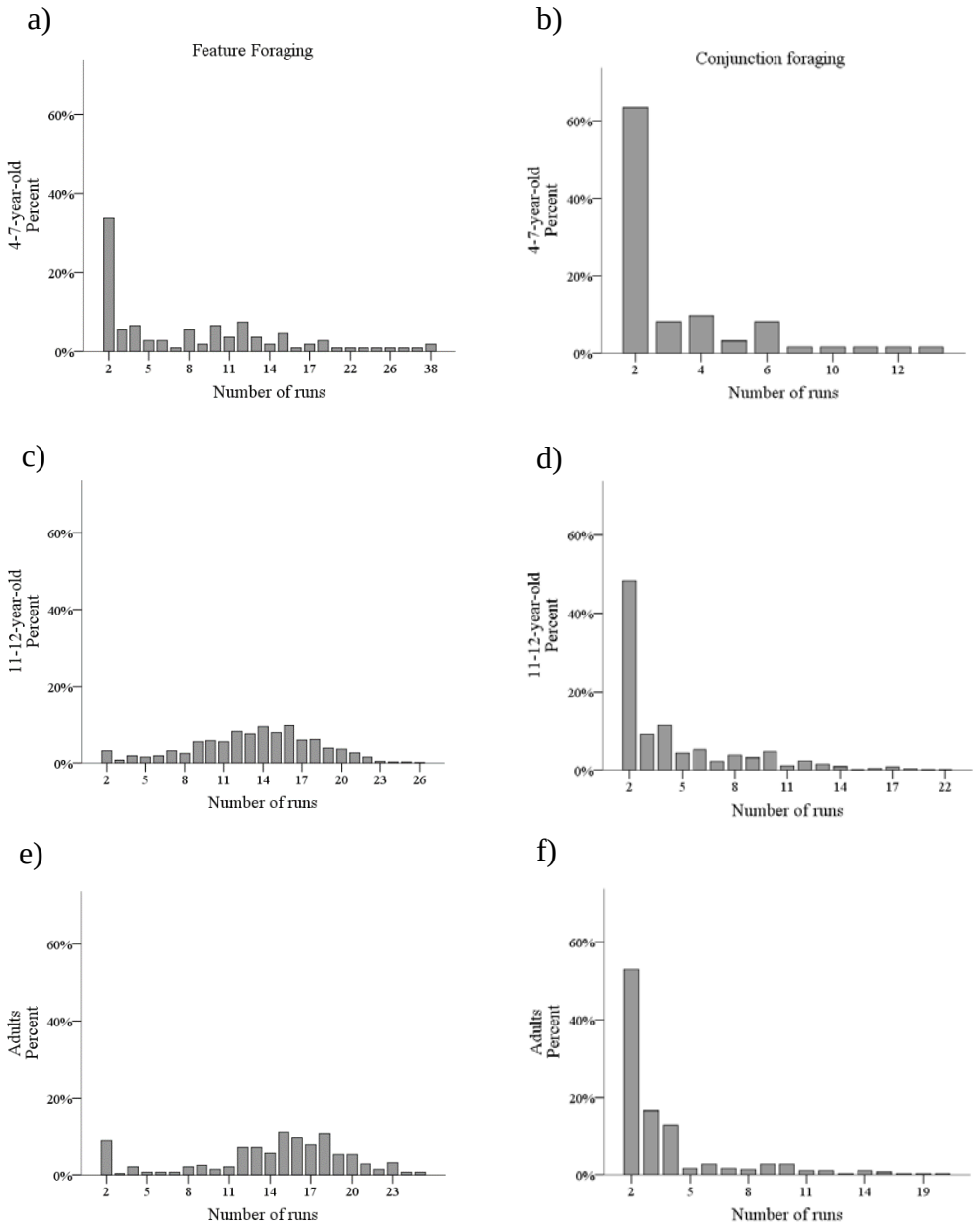

Figure 12. The distribution of the number of runs during feature (left) and conjunction foraging (right), collapsed over participants of each age group. **Panels a) and b)** show foraging for the 4–7-year-olds, **panels c) and d)** for the 11–12-year-olds, and the foraging of adults is shown in **panels e) and f)**.

3.4.2 Foraging speed and switch costs

The mean ITT per tap number was calculated for each age group. As panels a) and b) of Fig. 13 show, the 11–12-year-olds and adults have similar ITTs, but the young children were much slower during both foraging conditions. For each age group, the ITTs were similar throughout trials, except for distinct mid- and end peaks. End peaks occurred in both foraging conditions for all age groups, but are larger during conjunction than feature foraging, and much larger for the 4–7-year-old children than the other age groups. This may indicate a difficulty in finding the last target among many distractors. The mid peaks only occur during conjunction foraging for the 11–12-year-olds and adults but also appear during feature foraging for the 4–7-year-olds. Since most trials during conjunction foraging are completed in only two runs in all age groups, these mid peaks represent switch costs. This could also explain why there are mid-peaks during feature foraging for the 4–7-year-olds, because they completed the majority of the feature foraging trials in two runs, and they are the only age group that shows switch costs during feature foraging. In fact, when looking at witch costs (panels c) and d) of Fig. 13), there is a clear correspondence between the size of the switch costs and the mid peaks for each age group.

It is worth noting that the difference in mean ITTs between the feature and conjunction foraging trials mainly stem from the mid and end peaks. The remaining ITTs seem to be similar during feature and conjunction foraging (compare the ITTs of panels a) and b) in Fig. 13). The trials were split up in peaks vs. other taps and a three-way ANOVA with foraging condition, peaks, and age group as between-subjects factors was conducted. All main effects were significant (all *p*s < 0.001), meaning that there was an overall difference in ITTs between feature and conjunction foraging conditions, the peaks and other ITTs within a trial, and age groups (η_p^2s = 0.224, 0.461, and 0.536, respectively). Bonferroni post-hoc test revealed that the ITTs of the 4–7-year-olds differed from both other age groups (*p*s < 0.001), but no difference was found between the 11–12-year-olds and the adults. The interaction between peaks and age group was significant, $F(2, 149) = 40.07$, $p < 0.001$, $\eta_p^2 = 0.350$, meaning that when foraging condition is ignored, there is a greater difference between peaks and other ITTs within a trial for the youngest age group than the other two. There was also an interaction between foraging condition and peaks, $F(1, 149) = 38.84$, $p < 0.001$, $\eta_p^2 = 0.207$, meaning that regardless of age, the peaks are higher during conjunction than feature foraging. An interaction was also found between foraging condition and age, $F(2, 149) = 6.65$, $p = 0.002$, $\eta_p^2 = 0.082$, indicating that when the distinction between peaks

and no peaks is ignored, there is a greater difference between the ITTs of feature and conjunction foraging for the youngest participants than the older age groups. Finally, there was a three-way interaction between condition, peaks and age, F(2, 149) = 5.80, p = 0.004, η_p^2 = 0.072, indicating that the peak x condition interaction described above differed between the age groups. These differences can be seen in panels a) and b) in Fig. 13. In both foraging conditions, the peaks are much larger for the 4–7-year-olds than the others, as are the differences in the sizes of the peaks.

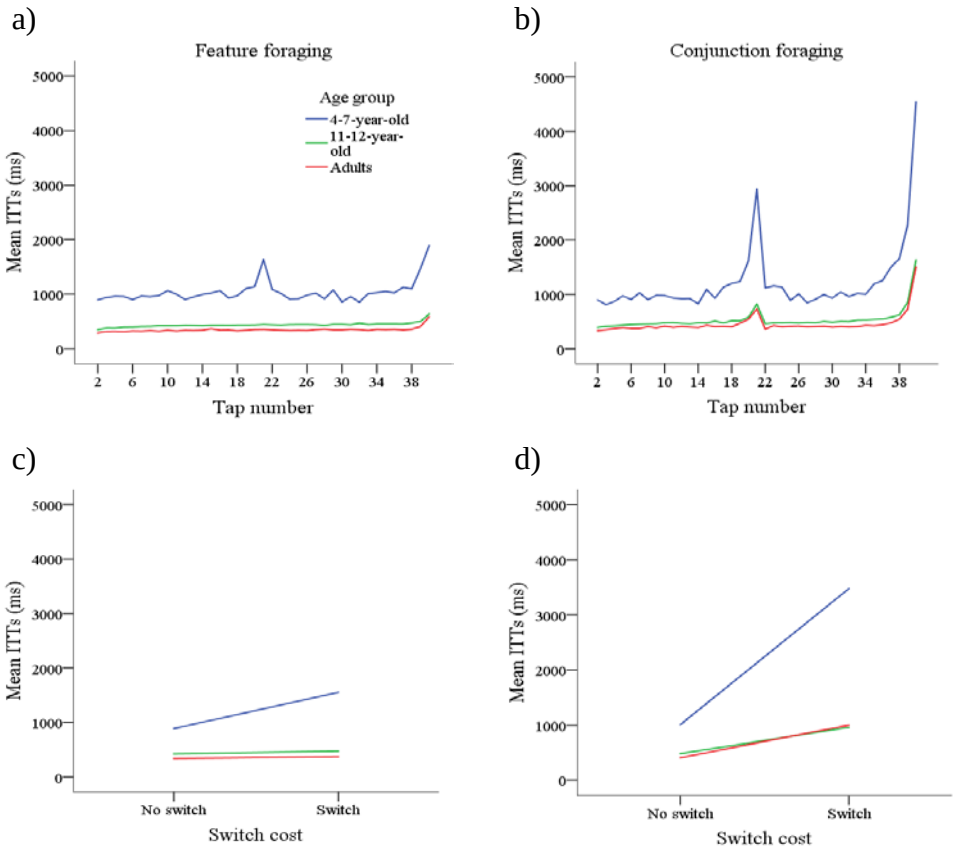

Figure 13. Comparison of the ITTs of 4–7-year-olds (blue lines), 11–12-year-olds (green lines), and adults red line) for the feature (left) and conjunction (right) foraging conditions. **Panels a) and b)** show the ITTs for every tap on a trial, and **panels c) and d)** show the switch costs for each age group. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Panels c) and d) in Fig. 13, show that switch costs are much higher during conjunction foraging for all age groups, highlighting the effort involved in switching between target categories during difficult tasks. This increased effort can, in turn, explain the long runs seen during conjunction foraging.

The switch costs of 11–12-year-old children are on par with those of adult participants, whereas the 4–7-year-old children show considerably larger switch costs during both feature and conjunction foraging. A three-way repeated measures ANOVA on condition and switch costs, with age as a between subjects factor, revealed significant main effects (all *p*s < 0.0001, η_p^2s = 0.500, 0.430, and 0.579, respectively). Bonferroni post-hoc comparisons revealed that the ITTs of the 4–7-year-olds differed from the other two age groups (*p*s < 0.001), but no difference was found between the 11–12-year-olds and the adults. All two-way interactions were also highly significant (all *p*s < 0.0001, condition × age η_p^2 = 0.354, switch cost × age η_p^2 = 0.398, and condition × switch cost η_p^2 = 0.405). Finally, the three-way interaction between condition, switch cost, and age was significant, F(2, 149) = 30.36, *p* < 0.001, η_p^2 = 0.289.

3.4.3 Foraging ability and executive functions

We explored the connection of executive functions and foraging with a series of multiple regression analyses. We predicted that greater EF abilities would be connected to faster ITTs, lower switch costs, and larger run numbers. Table 2 shows response times, error rates and standard deviations for the EF tasks, divided by age group. The youngest age group completed different EF tasks from the other two groups, so the comparison is restricted to 11–12-year-olds and adults. Independent samples t-tests revealed significant differences between the response times (RT) and error rates of the older children and the adults (Table 2).

A linear regression of the connection between EF and ITTs during feature and conjunction foraging revealed that different aspects of EF are connected to the foraging speed of 11–12-year-old children and adults (see Table 3). While attentional flexibility is the only EF that affects children's foraging speed, the speed of the adult participants depends partly on working memory. Inhibition did not affect the foraging speed of either age group.

No connection was found between error rates during foraging and EF measures (all *p*s > 0.05). Similarly, no connection was found between error rates of either EF task or foraging (all *p*s > 0.05). Therefore, error analyses will be excluded from the subsequent discussion.

Table 2. Means, error rates, and standard deviations of the executive functioning tasks.

	Mean (ms)	Standard deviation	Mean error rates	Standard deviation
11-12-year-olds				
Inhibition	125.21	63.55	1.07	1.45
Attentional flexibility	332.82	140.38	3.37	2.71
Working memory	2214.13	578.84	7.12	4.26
Adults				
Inhibition	51.19**	39.07	0.61*	0.80
Attentional flexibility	233.24**	87.24	2.35*	1.92
Working memory	1811.77**	459.98	4.00**	3.58

Note 1. The means reported for inhibition and attentional flexibility are the differences between response times during the baseline task and the tasks relying on inhibition and flexibility, thus reflecting the size of each effect regardless of the differences of overall speed for each individual. Note 2. The mean reported for working memory is the response times of correctly identifying a target (hits). Error rates in the working memory task reflect the number of misses.

* The differences between children and adults were statistically significant at 0.05.

** The differences between children and adults were statistically significant at 0.001.

Table 3. Linear regression of the effects of EF measures on ITTs of children and adults during feature and conjunction foraging.

	B	SE β	B	*p*
Feature foraging				
Children (11-12-year-old)				
Working memory	0.020	0.014	0.179	0.154
Inhibition	-0.127	0.146	-0.125	0.378
Attentional flexibility	0.165	0.069	0.358	**0.020**
Adults				
Working memory	0.049	0.019	0.444	**0.018**
Inhibition	-0.330	0.250	-0.256	0.199
Attentional flexibility	0.127	0.121	0.220	0.305
Conjunction foraging				
Children (11-12-year-old)				
Working memory	0.022	0.019	0.143	0.254
Inhibition	-0.141	0.200	-0.102	0.484
Attentional flexibility	0.226	0.095	0.360	**0.021**
Adults				
Working memory	0.111	0.032	0.600	**0.002**
Inhibition	-0.248	0.409	-0.114	0.549
Attentional flexibility	-0.018	0.198	-0.018	0.929

Note 1-feature foraging. R^2 = 0.160 for children (p = 0.012)*;* R^2 = 0.309 for adults *(*p = 0.017)
Note 2-conjunction foraging. R^2 = 0.148 for children (p = 0.019)*;* R^2 = 0.357 for adults *(*p = 0.007)

Attentional flexibility is defined as the ability to switch between two tasks and we believed that this measure would have the strongest connection to switch costs during foraging. Participants with the greatest attentional flexibility should, in other words, find it easiest to switch between target categories. As Table 4 shows, both working memory and attentional flexibility are connected to the time it takes children to switch between target types during feature foraging, but during conjunction foraging, attentional flexibility was the only EF measure that was related to switch costs. Inhibition does not seem to be related to children's switch costs in either foraging condition. No connection was found between EF and the switch costs of adult participants.

Table 4. Linear regression of the EF's influence on switch costs of children and adults during feature and conjunction foraging.

	B	SE β	B	*p*
Feature foraging				
Children (11-12-year-old)				
Working memory	0.015	0.007	0.249	**0.048**
Inhibition	-0.104	0.078	-0.191	0.187
Attentional flexibility	0.077	0.037	0.311	**0.042**
Adults				
Working memory	0.007	0.018	0.080	0.706
Inhibition	-0.153	0.232	-0.153	0.514
Attentional flexibility	0.042	0.112	0.093	0.714
Conjunction foraging				
Children (11-12-year-old)				
Working memory	-0.027	0.063	-0.051	0.670
Inhibition	-1.157	0.663	-0.242	0.086
Attentional flexibility	1.226	0.315	0.567	**0.000**
Adults				
Working memory	0.251	0.220	0.236	0.264
Inhibition	1.622	2.851	0.130	0.574
Attentional flexibility	-0.677	1.382	-0.121	0.628

Note 1-feature foraging. R^2 = 0.405 for children (p = 0.011)*;* R^2 = 0.027 for adults *(*p = 0.863)
Note 2-conjunction foraging. R^2 = 0.456 for children (p = 0.002)*;* R^2 = 0.052 for adults *(*p = 0.687)

Table 5 displays the connection between the EF measures and run number. We expected run number during feature foraging to be close to random, as participants would switch between target categories effortlessly and not surprisingly EF has no effect on either the children's or adults' run number during feature foraging. During conjunction foraging, however, we expected run number to be higher for participants with more developed EF abilities.

There is no effect of either attentional flexibility or inhibition for the children, and working memory has a very small, but significant, effect on run number, but in the wrong direction. This means that the longer the RTs are in the working memory task, the more often the participants switch between target categories. But a b of 0.001 is essentially a flat line and taking into account that the standard error is the same size, the significant *p*-value does not amount to much. For the adults, there is no effect of working memory or inhibition on the number of runs, but the effect of attentional flexibility approaches significance.

Table 5. Linear regression of the influence of EF's on the number of runs of children and adults during feature and conjunction foraging.

	B	SE β	B	*p*
Feature foraging				
Children (11-12-year-old)				
Working memory	-0.001	0.001	-0.127	0.336
Inhibition	0.007	0.007	0.154	0.316
Attentional flexibility	-0.004	0.003	-0.196	0.232
Adults				
Working memory	-0.001	0.002	-0.144	0.489
Inhibition	0.014	0.027	0.114	0.616
Attentional flexibility	-0.011	0.013	-0.199	0.422
Conjunction foraging				
Children (11-12-year-old)				
Working memory	0.001	0.001	0.269	**0.044**
Inhibition	-0.001	0.006	-0.024	0.873
Attentional flexibility	-0.001	0.003	-0.054	0.735
Adults				
Working memory	0.001	0.001	0.287	0.128
Inhibition	-0.008	0.011	-0.141	0.489
Attentional flexibility	-0.011	0.005	-0.442	*0.052*

Note 1-feature foraging. R^2 = 0.053 for children*;* R^2 = 0.068 for adults *(p*s > .05)
Note 2-conjunction foraging. R^2 = 0.066 for children (*p* = 0.236)*;* R^2 = 0.261 for adults (*p* = 0.040)

To summarize; attentional flexibility and working memory, but not inhibition, seem to affect ITTs and switch costs in both foraging conditions, but any effects of EF's on the number of runs seem at best to be small.

3.5 Discussion

Although interest in human foraging has increased in recent years, little is known about children's foraging and how it develops into adulthood. We had two main objectives; to continue the mapping of foraging abilities throughout

childhood and to assess the relation of foraging and EF abilities. Previous research on human foraging shows that for adult participants, foraging patterns are determined by task demands. When attentional load is high, most people tend to forage in long runs, but switch effortlessly between target categories when targets are easily distinguished (Jóhannesson et al., 2017; Kristjánsson et al., 2014). Here, the foraging patterns of 11–12-year-old children were similar to those of adults. The number of runs was close to random during feature foraging, but conjunction foraging trials mostly consisted of two runs. This pattern differs markedly from what was observed for the younger children, who tended to also forage in only two runs during feature foraging. As well as showing different foraging patterns, the younger children are also less effective foragers than the older children and adults with significantly higher switch costs, and slower overall foraging.

The general consensus is that when it comes to feature search, young children and infants perform similarly to older children and adults (Adler & Orprecio, 2006; Bhatt et al., 1999a, 1999b; Gerhardstein & Rovee-Collier, 2002; Thompson & Massaro, 1989; Trick & Enns, 1998). One study measured saccade latencies in three-month old infants and adults during feature and conjunction search tasks, to find out whether single features pop out for infants as they do for older children and adults. They found that like adults, infants do exhibit popout over the span of milliseconds, regardless of distractor set sizes (Adler & Orprecio, 2006). Similarly, when a visual search task with game-like features was administered to 12 to 36-month-old children to assess their performance in feature and conjunction search, their search slopes in the feature search task were relatively flat, suggesting that the same process is involved in feature search from infancy to adulthood (Gerhardstein & Rovee-Collier, 2002). By studying visual attention with a foraging task, we have found that young children do in fact have more difficulty with feature-based tasks than older children and adults, that are not only seen in higher ITTs, but also significantly increased switch costs and fewer runs per trial.

The foraging task also reveals that throughout most of the foraging trials (for all age groups) search times are very similar between the feature and conjunction tasks. The mid and end peaks mostly produce the differences in mean ITTs. In fact, T. Kristjánsson et al. (2018, see also Á. Kristjánsson et al., 2018) have found that by varying the set sizes of the foraging trials, the difference in the size of the end peaks closely resemble search slopes during feature and conjunction searches; end peaks during feature foraging remain the same size, but for conjunction foraging, the end peaks increase with set size. They speculate that these end peaks reflect performance in single-target

visual search, since they appear as participants search for a single target (the last target) among distractors. Thus, single target visual search paradigms may only provide a narrow window onto attentional orienting while foraging yields richer and more dynamic information.

By comparing the mid peaks of the three age groups, we found that they reflect the size of the switch costs, which are, in turn, connected to the number of runs. Larger switch costs highlight the effort involved in switching between target categories during difficult tasks. This increased effort can explain the long runs seen during conjunction foraging for all age groups and feature foraging of the 4–7-year-olds.

When children have turned 11 years old, their foraging patterns, ITTs, and switch costs are similar to adults. However, the relationship between foraging ability and EF, may reflect that children and adults using different mechanisms while completing the foraging tasks. The children with the greatest attentional flexibility were the fastest foragers (lowest ITTs), but no connection was found between attentional flexibility and ITTs in adults. Conversely, a connection was found between working memory and ITTs for the adult participants and not the children. This may be due to different developmental trajectories of different aspects of EF. Previous research has found that different subcomponents of EF are used in problem solving throughout development. Young children rely primarily on inhibition, and that focus gradually changes to attentional flexibility and then working memory over the course of development (Best et al., 2009; Huizinga & van der Molen, 2007; Senn et al., 2004). Huizinga and van der Molen (2007) compared performance on various EF tasks and the Wisconsin Card Sorting Test (WCST) for four age groups. They found that 7-year-old children relied heavily on inhibition and attentional flexibility while completing the WCST task, the performance of 11 and 15-year-olds was best predicted by attentional flexibility, but the 21- year-olds relied on working memory. The same thing may occur during foraging, where 11–12-year-old children rely on attentional flexibility, and adults on working memory, to successfully complete the same task.

No connection was found between EF and the switch costs of adults. For the children, both attentional flexibility and working memory affected switch costs during feature foraging, but during conjunction foraging the effect of working memory disappeared, while the connection with attentional flexibility grew stronger. This most likely reflects that the children keep both target items in mind during feature foraging but switch between target templates during conjunction foraging. Working memory load during conjunction foraging is

presumably much higher than during feature foraging (see Awh & Jonides, 2001; Kristjánsson et al., 2014). We speculate that during the easier foraging task, the children with the greatest working memory capacity have an advantage because they can more easily maintain the target categories in working memory, allowing faster switches between the categories. During conjunction foraging, working memory is no longer connected to switch costs, which may indicate that the children find it difficult to hold two conjunction targets in mind.

Note that in a recent study, Jóhannesson et al. (2017) investigated the effects of inhibition and working memory on foraging patterns, finding no connection. They divided their participants, based on the number of runs, into “super-foragers” and “normal-foragers” (Kristjánsson et al., 2014) and tried to find differences in EF abilities between those groups. But the group comparison may not have been sensitive enough to assess the connection between EF and foraging, since foraging patterns may not have differed by enough between the groups. We believed that a regression analysis would be better suited to find any existing connection. We predicted that attentional flexibility would facilitate switching between target types, and greater inhibition would counter the preference for tapping the targets of the same type as previously attended (Brascamp et al., 2011; Chetverikov & Kristjánsson, 2015), affecting the number of runs during conjunction foraging. There was no connection between children's number of runs and EF, but attentional flexibility seems to have some effect on the number of runs of adults during conjunction foraging.

No connection was found between inhibition and foraging (in line with Jóhannesson et al., 2017). Note that the task in neither study involved a pure measure of inhibition, but a complex conflict task, which requires the participants to inhibit a prepotent response and produce an alternative one that conflicts with it, as well as remembering an arbitrary rule, which requires working memory (Best & Miller, 2010). In fact, previous research has revealed that tasks that simply require withholding a prepotent response, load on a different factor from tasks requiring conflicted responding (Carlson & Moses, 2001). Inhibition should therefore be assessed in a simple task involving withholding a prepotent response, ensuring no confounding of inhibition with other functions, such as working memory for definite conclusions. Likewise, inhibition seems to play a large role in the EF of young children (Senn et al., 2004) so it would be interesting to assess the connection between inhibition and foraging in younger populations.

3.6 Conclusions

Foraging patterns, foraging speed, and switch costs of 11–12-year-old children differ from those found for 4–7-year-old children and are much more similar to those seen for adult participants. By using a foraging task instead of a single target visual search task, we have found that young children do have more difficulty than their older counterparts completing feature-based tasks, not only reflected in slower foraging, but also with higher switch costs and different foraging patterns. Additionally, a connection was established between foraging and EF, where all aspects of foraging ability measured in the current study show a connection to either working memory, attentional flexibility, or both, but inhibition was not found to affect foraging. Lastly, the connection between foraging and EF showed different patterns in children and adults, likely reflecting different developmental trajectories of EF subcomponents. More foraging research is needed to fully grasp the complex relationship between these factors.

4 Paper II

The following chapter is a manuscript published in the Journal of Experimental Child Psychology under the name Age differences in foraging and executive functions: A cross-sectional study. The authors are Ólafsdóttir, I. M., Gestsdóttir, S. & Kristjánsson, Á. Figure numbers, references and some formatting has been changed from the published paper for continuity with the thesis as a whole. Any references to content within this chapter should be as follows:

Ólafsdóttir, I. M., Gestsdóttir, S., & Kristjánsson, Á. (2020). Age differences in foraging and executive functions: A cross-sectional study. *Journal of Experimental Child Psychology*, *198*, 104910.

4.1 Abstract

Visual foraging tasks require participants to search for multiple targets among numerous distractors. Foraging paradigms enable insights into the function of visual attention above what has been learned from traditional single-target search paradigms. These include attentional orienting over time and search strategies involving target selection from different target types. To date, only a handful of studies have been conducted on the development of foraging abilities. Here, the foraging of five age groups—children aged 6, 9, 12, and 15 years and adults—was measured, as was their performance on various tasks assessing four subdomains of executive functions: inhibition, attentional flexibility, working memory, and problem solving. Executive functions consist of a complex network of independent but interconnected cognitive processes that regulate action-orienting and goal-directed behavior and have been shown to be connected to visual attention and attentional orienting. Our results show that foraging abilities improve dramatically from 6 to 12 years of age, when adult levels of foraging have been reached. This is evident from reduced foraging times, increasingly frequent switches between target types, lower switch costs, and reduced error rates. In addition, partial least squares structural equation modeling reveals that the age differences on the foraging tasks are predominantly indirect effects through executive functions. In other words, the development of successful foraging abilities is highly correlated with the maturation of executive functions.

4.2 Introduction

Imagine that you're sitting with a child, playing with LEGOs. The child decides that she wants to build a white house with a red roof and starts sifting through the LEGOs, separating the red and white ones from blocks of other colors. This is an example of foraging, defined as continuous search for multiple target items among multiple distractors (Kristjánsson er al., 2014; Ólafsdóttir et al., 2016, 2019; Wolfe, 2013; see review in Kristjánsson et al., 2019). The task requires many cognitive operations such as recognizing the relevant blocks and guiding gaze and hands toward them while avoiding other blocks, operations that are typically thought to involve executive functions and attention.

Although there is a long tradition of assessing visual attention with single-target visual search tasks (Bravo & Nakayama, 1992; Treisman & Gelade, 1980; Wolfe, 1994; see recent reviews in Kristjánsson, 2015; Kristjánsson & Egeth, 2020; Wolfe & Horowitz, 2017), recent studies of multitarget visual foraging have allowed the study of attentional orienting over time with a more dynamic task than when only a single target is to be found. This line of research originates from studies on animals that forage for food in the wild (see, e.g., Bukovinszky et al., 2017; Dawkins, 1971; Mallott et al., 2017; Pyke et al., 1977), but computerized foraging tasks where humans are tested have more recently been introduced (Kristjánsson et al., 2014; Wolfe, 2013). Studying visual attention by using foraging tasks enables investigation of how attention is allocated over time and how people attend to multiple targets that differ by type. This allows for inquiries into, for example, how and when people switch between target types and the cost of switching in addition to more traditional measures of visual attention such as response times (RTs) and the differences between performance on tasks with high and low attentional loads.

4.2.1 Attentional load and foraging

It is well established that manipulating the attentional load of a task alters participants' performance. For instance, when observers search for a target that is distinguished from distractors by a single feature, it tends to ‘‘pop out" and the search is fast and effortless regardless of the number of distractors in the display (Maljkovic & Nakayama, 1994; Treisman & Gelade, 1980). However, when targets are defined by a conjunction of features and therefore attentional load is higher, search times increase as a function of the number of distractors (Treisman & Gelade, 1980; Wolfe, 1994; see Kristjánsson & Egeth, 2020, for a recent review). Continuing with our LEGO analogy, foraging for

white and red LEGOs would be an example of a feature foraging task, where the blocks are distinguished from distractors by a single feature, in this case color. But when the house in our example is almost ready, we might need only square blocks. Now the task has turned into a conjunction foraging task, where the targets are defined by both color and shape. Foraging studies using this feature–conjunction manipulation have shown that throughout foraging trials where observers must find all targets of a particular type, inter-target times (ITTs; the times between taps on a target) of feature and conjunction trials are typically very similar. The largest differences in completion times between these paradigms stem from distinct peaks or rises in ITTs of conjunction foraging trials that appear when observers switch between target types and at the end of each trial (T. Kristjánsson et al., 2018, 2020a; Ólafsdóttir et al., 2019). End peaks also appear for feature foraging but tend to be much smaller than during conjunction foraging. Interestingly, end peaks during conjunction, but not during feature foraging, become larger as the distractor number rises, corresponding well with how RTs rise in accordance with the number of distractors in single-target conjunction search (T. Kristjánsson et al., 2020a). Another useful measure in foraging tasks involves the number of runs per trial, which provides important information about foraging strategies. A run is defined as the consecutive selection of the same target type. The more frequently an observer switches between target types during a trial, the more runs in which the trial will be completed. Kristjánsson et al. (2014) found that the number of runs per trial is affected by attentional load. When targets are defined by a single feature and attentional load is low, switching between target types typically occurs at random, but when targets are defined by a conjunction of features and attentional load is higher, participants tend to repeatedly select the same target type, thereby completing most foraging trials in two runs. The insights from these foraging paradigms demonstrate the added information gained from studying visual attention over time with dynamic tasks and the importance of investigating constructs from varied perspectives.

4.2.2 Development of visual attention

As with the literature on adult observers, the development of visual attention during childhood has mainly been investigated with single-target search tasks. A common finding is that young children have difficulty in finding targets defined by a conjunction of features (Donnelly et al., 2007; Merrill & Conners, 2013; Merrill & Lookadoo, 2004; Taylor et al., 2003; Trick & Enns, 1998; Woods et al., 2013). In those tasks, even when there are only two items on the screen—one target and one distractor—search times of children younger than 10 years tend to be approximately double the search times of young adults

(see, e.g., Hommel et al., 2004; Trick & Enns, 1998). Plots displaying RTs against set size provide information about how adding distractors to displays affects search. In conjunction search tasks, plotting the RT against the number of distractors tends to result in steep slopes, but in feature search tasks they are flat, meaning that no matter how many distractors appear, the target pops out and RTs do not increase. Children's search slopes during conjunction search tasks tend to be much steeper than those of young adults, emphasizing the difficulties they have with the tasks (Merrill & Conners, 2013; Merrill & Lookadoo, 2004; Trick & Enns, 1998). Children's performance on feature-based search tasks, on the other hand, is similar to that of adults; children's search slopes are relatively flat (Donnelly et al., 2007; Merrill & Conners, 2013), even for toddlers (Gerhardstein & Rovee-Collier, 2002) and infants as young as 2 months (Adler & Orprecio, 2006). These results suggest that feature- and conjunction-based search tasks rely on different mechanisms and that abilities for feature search are innate or develop during the first few months of life, whereas mechanisms necessary for conjunction search mature slowly and continue to develop throughout childhood (see, e.g., Gerhardstein & Rovee-Collier, 2002; Taylor et al., 2003).

However, Ólafsdóttir et al. (2016, 2019) found that, in contrast to single-target visual search studies (Donnelly et al., 2007; Gerhardstein & Rovee-Collier, 2002; Merrill & Conners, 2013; Merrill & Lookadoo, 2004), young children have more difficulty than adults in finding targets that are defined by only a single feature. Adult observers tend to switch randomly between target types during feature foraging, and switch costs are small (Kristjánsson et al., 2014; Ólafsdóttir et al., 2019), whereas young children tend to forage in long runs and switches between target types result in considerably slowed foraging (Ólafsdóttir et al., 2016, 2019; see also Gil-Gómez de Liaño et al., 2018).

4.2.3 Executive functions

Previous research has established that the development of visual attention is at least partly dependent on executive functions (Jenkins & Berthier, 2014; Longstaffe et al., 2014; Trick & Enns, 1998; Woods et al., 2013). Executive functions consist of distinct but interconnected cognitive mechanisms that control action-orienting and goal-directed behaviors (Anderson, 2002; Best et al., 2009; Miyake et al., 2000). Whereas early research focused on whether executive functions could be considered a unitary construct or consist of separate components, recent disputes have focused on which cognitive processes comprise the executive functioning network and how they relate to one another (Best & Miller, 2010; Best et al., 2009; Brocki & Bohlin, 2004; Wu

et al., 2011). During recent years, a general consensus seems to have emerged that working memory, inhibition, and attentional flexibility are core functions in this network (Best & Miller, 2010; Best et al., 2009; Miyake et al., 2000; Zelazo, 2015; Zelazo et al., 2016).

Working memory refers to the ability to update, maintain, and manipulate information in memory. Inhibition is the capability to refrain from prepotent responses when required. Attentional flexibility, or shifting, is the ability to switch between mental sets or tasks, disengaging from one aspect of a task and engaging with another one (Lee et al., 2013; Wu et al., 2011). These different aspects or subcomponents of executive functions mature at different rates (Diamond, 2002; Isquith et al., 2004; Wu et al., 2011; for reviews, see Best & Miller, 2010; Best et al., 2009), which supports the argument that executive functions are not a unitary construct but rather a network of distinct but interconnected components (Best et al., 2009). Inhibition develops rapidly at an early age, but improvement slows down considerably after the preschool years (Davidson et al., 2006; Klenberg et al., 2001; Pureza et al., 2013). In relatively simple inhibition tasks, adult levels of performance are frequently reported to have been reached at around 12 years of age (Brocki & Bohlin, 2004; Huizinga et al., 2006; Wu et al., 2011), but some studies have found ceiling effects of performance even earlier such as at 6 years (Klenberg et al., 2001) or 7 years (Johnstone et al., 2007). In more complex tasks, continued improvements can be seen into adolescence (Huizinga et al., 2006) and even early adulthood (Huizinga et al., 2006; Leon-Carrion et al., 2004). Working memory develops later than inhibition and shows linear improvement into adolescence (Gathercole et al., 2004; Lee et al., 2013). Attentional flexibility appears to be dependent on inhibition and working memory given that task switching includes remembering a set of rules and suppressing a previous mental set and/or response in order to produce the new one (Davidson et al., 2006; Diamond, 2002; Miyake et al., 2000). Like working memory, attentional flexibility continues to improve throughout adolescence (Anderson, 2002; Davidson et al., 2006; Huizinga et al., 2006).

Tasks that measure complex executive functions, such as planning and problem solving, also seem to tax the core executive functions described above (Best et al., 2009). In these tasks, observers must find a strategy for completing the task, remember this strategy, evaluate progress, switch tactics if needed, and even inhibit responses to evaluate their merit. Planning and organization seem to mature at a later age than the core executive functions (Huizinga et al., 2006; Pureza et al., 2013). These skills develop rapidly from 7 to 10 years of age, but a regression in performance has been reported from

11 to 13 years, when children prefer cautious and conservative approaches (Anderson, 2002). Continued improvements in problem-solving abilities are then observed into adulthood (Huizinga et al., 2006; Pureza et al., 2013).

Notably, all these executive function abilities are important for efficient visual foraging. Findings from the visual search literature show that observers tend to attend preferentially to the same type of targets as have been attended before (Brascamp et al., 2011; Chetverikov & Kristjánsson, 2015; see Ásgeirsson & Kristjánsson, 2019, for a review). Inhibiting ‘‘primed” responses could facilitate switching between target types. In addition, inhibition should lower erroneous taps on distractors. Working memory is considered necessary for maintaining templates of targets (Awh & Jonides, 2001; Bundesen, 1990). Attentional flexibility should facilitate switching between target types (Huizinga et al., 2006), resulting in more runs and lower switch costs. Problem-solving abilities should help observers to formulate and evaluate strategies for trial completion (Pureza et al., 2013), resulting in fewer errors and faster foraging. Although these functions can be measured independently, it is important to note that they are interconnected. Indeed, even though studies on adults have supported Miyake et al. (2000) three-factor model of executive functions, some studies on children have found that a one-factor model fits the data best when preschool-aged children are tested (Wiebe et al., 2011; Willoughby et al., 2010, 2012), and a two-factor structure is more reflective of executive functions up to 15 years of age (Lee et al., 2013). All in all, regardless of whether the subcomponents of executive functions are measured separately or in combination, greater executive functioning abilities should contribute to more successful foraging.

4.2.4 The current study

Although our previous studies (Ólafsdóttir et al., 2016, 2019) have provided important information about the relation between foraging performance and executive functions among young children aged 4 to 7 years as well as among children aged 11 and 12 years, a direct comparison for a number of different age groups is needed for a clearer picture. In the current study, we assessed the foraging performance and executive functions of five different age groups ranging from 6 years to adulthood. To our knowledge, this is the first comprehensive cross-sectional study of cognitive development and visual foraging. Our aim was to provide answers to important questions about whether executive functions affect attentional orienting. Previous studies have mainly used single-target visual search tasks but using the foraging task allows for more diverse performance assessment because of the many dependent

measures involved in the paradigm.

Regarding foraging performance, we expected to replicate previous results (Ólafsdóttir et al., 2016, 2019) and see improvements in all aspects of the foraging task up until 12 years of age, when children should have reached adult levels of performance. In line with previous research (Kristjánsson et al., 2014, T. Kristjánsson et al., 2018; Ólafsdóttir et al., 2016, 2019), we expected feature foraging trials to be completed with greater ease than conjunction foraging trials, resulting in more runs per trial, faster foraging, and lower switch costs and error rates. We expected to see these differences between the two foraging conditions across all age groups.

Lastly, we explored the connection among foraging performance, age, and executive functions with partial least squares structural equation modeling (PLS–SEM). Some previous studies have not shown any connection between executive functions and foraging (Jóhannesson et al., 2017), whereas others have shown that attentional flexibility (Ólafsdóttir et al., 2019) and/or working memory (Ólafsdóttir et al., 2016, 2019; Quirós-Godoy et al., 2018) affect foraging performance. We expected to find that age affects both executive functions and foraging and that executive functions affect foraging above and beyond the effects of age.

4.3 Method

4.3.1 Participants

A total of 86 participants from five age groups partook in the study: children aged 6, 9, 12, and 15 years and adults (see Table 6). The children came from two schools in the same school district of Reykjavík, Iceland. All the children in each age group were in the same school year. The adult group consisted of 23 undergraduate students. Data from 3 adult participants were removed due to color blindness. All remaining participants had normal or corrected-to-normal eyesight.

Information about the study and consent forms were sent home with all the children for their parents to sign. Children aged 12 and 15 years were asked to give their assent by signing the forms along with their parents, and verbal assent was obtained from the 6- and 9-year-old children.

The adult participants were students in an undergraduate class in psychology and were offered class credit for their participation in the study. The children did not receive any compensation for their participation. All aspects of the experiment were reviewed and approved by the Icelandic

National Bioethics Committee and the data protection authority, and permission was granted by the Reykjavik Department of Education and Youth as well as by both school administrations.

Table 6. Participant characteristics.

	Number of participants	Age span	Mean age (years)	Sd (years)	Gender
6 years	18	5.84-6.69	6.24	0.30	10 girls/ 8 boys
9 years	16	9.06-9.78	9.44	0.22	11 girls/ 5 boys
12 years	16	11.92-12.78	12.29	0.27	11 girls/ 5 boys
15 years	16	14.93-15.81	15.42	0.28	12 girls/ 4 boys
Adult	20	21.88-48.63	25.55	6.03	12 female/ 8 male

4.3.2 Experimental settings

The experiment was run in a quiet room with normal illumination. The adult participants were tested in the lab, whereas the children were tested 2 at a time at their school, with 1 participant starting with the Tower of London and foraging tasks and the other participant starting with the executive function tasks. The 6-year-old participants finished two 25-min sessions on different days, with a maximum of 1 week between them. They completed the foraging and Tower of London tasks in one session and completed the three executive function tasks in the other session. The older children and adults completed all tasks in one 40- to 50-min session. The order of all tasks was counterbalanced, as were the foraging condition and the color and shape of targets and distractors during foraging. Each task started with a few practice trials.

4.3.3 The foraging task

4.3.3.1 Equipment

The foraging task was presented on an iPad 2, with screen dimensions of 20 x 15 cm and an effective resolution of 1024 x 768 pixels, placed on a table in front of participants in landscape mode so that viewing distance was approximately 50 cm. Stimulus presentation and response collection were carried out with a custom iPad application written in Swift using Xcode.

4.3.3.2 Stimuli and measures

Each trial started with 40 stimuli on a black background, half of which were targets and half of which were distractors. On feature foraging trials, the stimuli were red, green, yellow, and blue discs. On conjunction foraging trials, the stimuli were red and green discs and squares. Their diameter was 20 pixels (~0.46° visual angle). The items were distributed randomly on a nonvisible 10 x 8 grid and offset from the screen edge by 100 x 150 pixels. The viewing area therefore occupied 12 x 15 cm (~13.7 x 17.1°). The position of each item within the grid was randomized by adding a random vertical and horizontal offset. Gaps between columns and rows ensured that items never occluded or approached one another. The location of the targets and distractors was randomly generated from trial to trial (see Fig. 14).

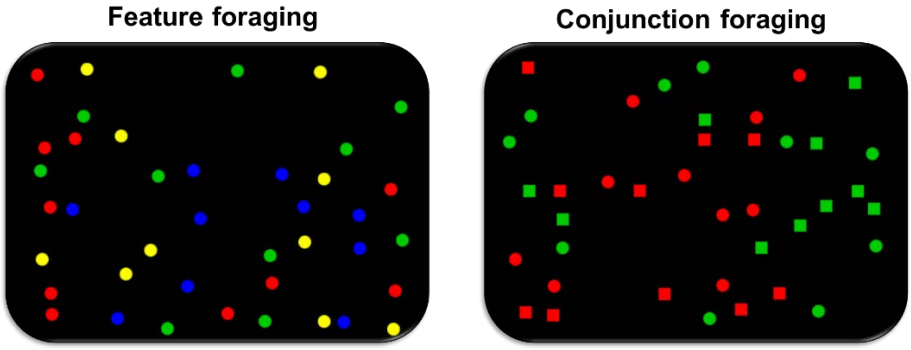

Figure 14. Screenshots of the foraging task. The **left panel** shows a feature foraging trial, and the **right panel** shows a conjunction foraging trial.

4.3.4 Executive functions

4.3.4.1 Equipment

The computerized executive function tasks were administered on a 17.3-inch laptop computer screen with an effective resolution of 1600 x 900 pixels. Task presentation and response collection were carried out with the Amsterdam Neuropsychological Tasks (ANT) program (De Sonneville, 1999).

The Tower of London DX–Second Edition (Culbertson & Zillmer, 2005) consisted of two wooden tower structure boards and two sets of plastic beads, scoring sheets, and a stopwatch.

4.3.4.2 Stimuli and measures

The ANT program is a test battery containing 38 tasks developed to assess neuropsychological functions of children and adults aged 3 to 80 years. The test battery enables the evaluation of various aspects of attention, information processing, and executive functions (De Sonneville, 1999).

4.3.4.3 Procedure

Three tasks from the ANT tasks program were administered to measure inhibition, attentional flexibility, and working memory. The Tower of London task was administered to measure problem solving.

Go/no-go. In this task, a gray square with wide yellow borders appears on a black background. Either the border can surround the square or there can be a gap in the middle of its bottom line (see Fig. 15). The go/no-go task measures simple inhibition. The only requirement for the task is inhibition of prepotent responses without confounding from other functions such as working memory (Best et al., 2009).

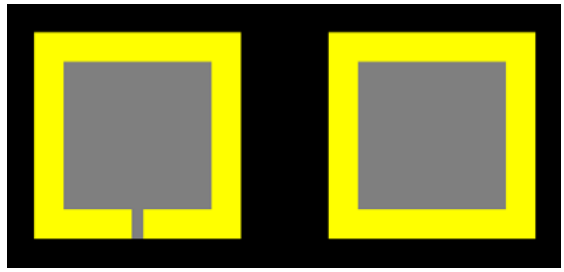

Figure 15. The two squares that were presented in the go/no-go task. The left panel shows the square that represented ‘‘go” trials, and the right panel shows the square that represented ‘‘no-go” trials. [Figure reproduced from the Amsterdam Neuropsychological Tasks (ANT) manual (De Sonneville, 2011)].

Participants were asked to look at the squares carefully and were informed that a square would appear in the middle of a black screen. If it had a notch in it (75% of trials), participants were asked to press a button on the keyboard as quickly as possible but to do nothing if it did not (25% of trials). The response key was always on the same side of the keyboard as participants’ dominant hand. The squares appeared in a pseudorandom order, and each presentation lasted 800 ms or until a response was made. Participants performed 48 trials.

Attentional flexibility. In this task, a disc appears to the left or right of a

white fixation cross on a black background. In the first part, the disc is always green, and participants are asked to press the response key on the same side as the disc appears. In the second part, the disc was always red, and participants were asked to press the response key on the opposite side. In the third part, the disc could be either red or green. The first part assesses baseline response speed. The second part assesses inhibition of prepotent responses and the production of alternate ones, which can be classified as a complex inhibition task (see, e.g. Best et al., 2009). The third part assesses set shifting, where participants need to hold two rules in mind and switch between them according to which stimulus appears on the screen. The discs remained on the screen until participants pressed a response button, but for a maximum of 7000 ms if no response was made. Responses were valid if they occurred from 200 to 6000 ms after stimulus appearance. The intertrial interval was 1200 ms. If a participant missed a trial, a trial was added at the end of the session to ensure that response numbers were the same for all participants. Before each part, participants were given instructions about the stimuli and how to respond. The first two parts consisted of 30 trials each and the third part consisted of 60 trials, so that each color appeared 30 times (the side they appeared on and their color in the third part in pseudorandom order).

Working memory. The memory search task assesses the maintenance and uploading of working memory content. Participants were asked to memorize a geometric colored shape (e.g., a blue square). Four geometric shapes appeared on a black screen, and participants were instructed to press a key if the memorized shape was among the four shapes and to press a different key if not. In the second part, participants were asked to memorize three different colored shapes. If at least one of the memorized shapes appeared on the screen, participants were instructed to press a particular key and to press a different key if none of the shapes appeared. The key indicating the ‘‘yes” response was always on the same side as participants’ dominant hand. The shapes appeared in pseudorandom order, with a target present on half of the trials. They remained on the screen until a response was made, but for a maximum of 7000 ms. A mask appeared for 1200 ms before the next trial started. Responses were valid if they occurred from 200 to 6000 ms after the stimuli appeared. Each part of the task started with 12 practice trials, after which participants were asked whether they still remembered the shape(s) and were allowed to look at them again before the task started. Each part of the session was 48 trials, but if no response was made, the same shapes appeared again at a different location, holding the number of responses constant across participants.

Problem solving. Lastly, The Tower of London DX–Second Edition measures higher order problem-solving ability. Participants are required to develop an action plan, identify subgoals, organize them, and self-monitor their progress while maintaining the solution in working memory (Culbertson & Zillmer, 2005).

The researcher and each participant sat opposite each other, with both having a wooden board with three pegs of different sizes in front of them. The researcher explained that they would arrange the beads on the pegs in different patterns and that the participant should make the same patterns on his or her own board by using as few moves as possible. There were 2 practice trials before 10 experimental trials. The trials became more complicated as the task progressed. The researcher counted the number of moves and timed the participant. If the participant took longer than 2 min to complete a trial, the researcher invited him or her to try the next one.

4.3.5 Data analysis

4.3.5.1 Foraging

The measures of the foraging task involve (a) ITTs, where an ITT is defined as the time that passes between each tap on a target; (b) number of runs, where a run is defined as the consecutive selection of the same target type (with two target types, 10 of each, the minimum run number is 2 if all targets of one type are tapped before the observer switches to the next target type; the maximum run number is 20 if the observer always switches between target types); (c) switch costs, which are calculated by finding the mean ITTs of the first tap in each run, where the participant switches from the other target type, and the mean ITTs of the consecutive taps within the run and then subtracting the latter from the former; and (d) error rates, involving how often the observer tapped a distractor.

The first trial of each foraging condition (feature and conjunction) was regarded as a practice trial and removed from the data set. A series of mixed-measures analyses of variance (ANOVAs) with Tukey HSD (honestly significant difference) post hoc comparisons were run to assess both age differences in foraging and differences between foraging conditions.

4.3.5.2 Executive functions

To measure attentional flexibility, the RTs of correct trials in the first part of the attentional flexibility task, which measures baseline speed, were subtracted from the RTs of correct trials in the third part, where the task demands changed

constantly (see, e.g., Brunnekreef et al., 2007, Mesotten et al., 2012, and Schuitema et al., 2013, for previous research using the same method). By subtracting baseline speed from the RTs of the third part of the task, individual differences in response speed are controlled and a purer measure of how switching between task objectives slows down responses is obtained. The number of false alarms was used to assess performance in the go/no-go task. Preliminary analyses of data from the working memory task showed error rates of about 20% with no intergroup differences. Therefore, RTs of hits (correct target-present trials) were used to measure age differences. The number of moves in the Tower of London task was used as a measure of problemsolving ability.

Due to collinearity of the executive function measures and a relatively small sample size, reflective PLS–SEM was used to explore the relationship between executive functions and foraging. PLS–SEM is a dimension reduction method that combines principal component analysis (PCA) and regression-based path analysis to estimate partial model structures (Hair et al., 2019; Ringle et al., 2020). As in PCA, PLS–SEM combines indicator variables linearly to use as proxies for components, or latent variables, that are believed to explain the variance of target constructs in the model (Ali et al., 2018). The difference is that with the PLS–SEM method, instead of maximizing the explained variance of the independent variables, the latent variables are created by minimizing the error variance of the dependent variables (Geladi & Kowalski, 1986). This method is often viewed as an alternative to covariance-based SEM (CB–SEM; Jöreskog, 1973), which considers only the common variance of the data in estimating model parameters. PLS–SEM, on the other hand, accounts for the total variance and uses it to estimate parameters (Hair et al., 2019). PLS–SEM avoids numerous restrictions of CB–SEM such as sample size requirements and assumptions about residual distribution and observational independence (Chin, 1998; Ringle et al., 2020). Therefore, the PLS–SEM method can be used with small sample sizes and is an appealing option when dealing with collinearity as in the current data set (Henseler et al., 2009).

Bias-corrected and accelerated bootstrapping with 10,000 subsamples was used to carry out significance testing. To evaluate the model's predictive powers, both blindfolding and PLSpredict were carried out. Blindfolding is a method for obtaining cross-validated redundancy and communality of both latent variables and indicators. The omission distance was set at 7, which means that the algorithm omits every seventh data point of the indicators and does seven iterations. Estimates from these iterations are combined to

compute the Stone–Geisser Q^2, which is the cross-validated redundancy of a reflectively modeled latent variable. Smaller differences in original and predicted values result in higher Q^2 values, indicating greater predictive power (Geisser, 1974; Ringle et al., 2020; Sarstedt et al., 2014; Stone, 1974).

PLSpredict uses k-fold cross-validation, where the data set is split into k equally sized subgroups and combines 1 - k subgroups into a training sample, which then predicts the remaining subgroup. The cross-validation is then repeated k times so that each subgroup will be left out of the training sample once (Shmueli et al., 2019). It is important to ensure that the training sample size meets the minimum sample size requirements for the model. In the current study, the k value was set to 10, which is the convention if sample size allows for it (Shmueli et al., 2019).

4.4 Results

4.4.1 Age differences in foraging

Fig. 16 shows four measures of foraging performance by age and foraging condition. Foraging improved with age in all measures. Older participants foraged more quickly, F(4, 81) = 67.092, $p < .001$, $\eta_p^2 = .768$, and their switch costs and error rates were lower, F(4, 81) = 12.101, $p < .001$, $\eta_p^2 = .374$ and F(4, 81) = 9.782, $p < .001$, $\eta_p^2 = .326$, respectively. Older participants were also more prone to switching between target types within trials, resulting in higher run numbers, F(4, 81) = 6.660, $p < .001$, $\eta_p^2 = .247$. Fig. 16 also reveals large the number of runs by foraging condition, F(1, 81) = 132.651, $p < .001$, $\eta_p^2 = .621$, but there was no interaction with age ($p = .105$). There was also a difference in foraging speed by condition, F(1, 81) = 214.703, $p < .001$, $\eta_p^2 = .726$, with participants of all ages foraging more quickly during feature foraging (see Fig. 16). The interaction between condition and groups was also significant, differences between foraging conditions; there was a significant difference in F(4, 81) = 8.296, $p < .001$, $\eta_p^2 = .291$. The difference in switch costs between foraging conditions was also significant, F(1, 81) = 98.076, $p < .001$, $\eta_p^2 = .548$, as was the interaction between age and foraging condition, F(4, 81) = 3.178, $p = .018$, $\eta_p^2 = .136$. Lastly, there was a significant difference in error rates between foraging conditions, F(1, 81) = 50.505, $p < .001$, $\eta_p^2 = .384$, with an interaction between age and foraging condition, F(4, 81) = 7.383, $p < .001$, $\eta_p^2 = .267$.

A Tukey HSD post hoc comparison of the age differences showed that they are mainly due to 6- and 9-year-old children performing differently from the older age groups (see Table 7). The 6-year-olds were the slowest foragers

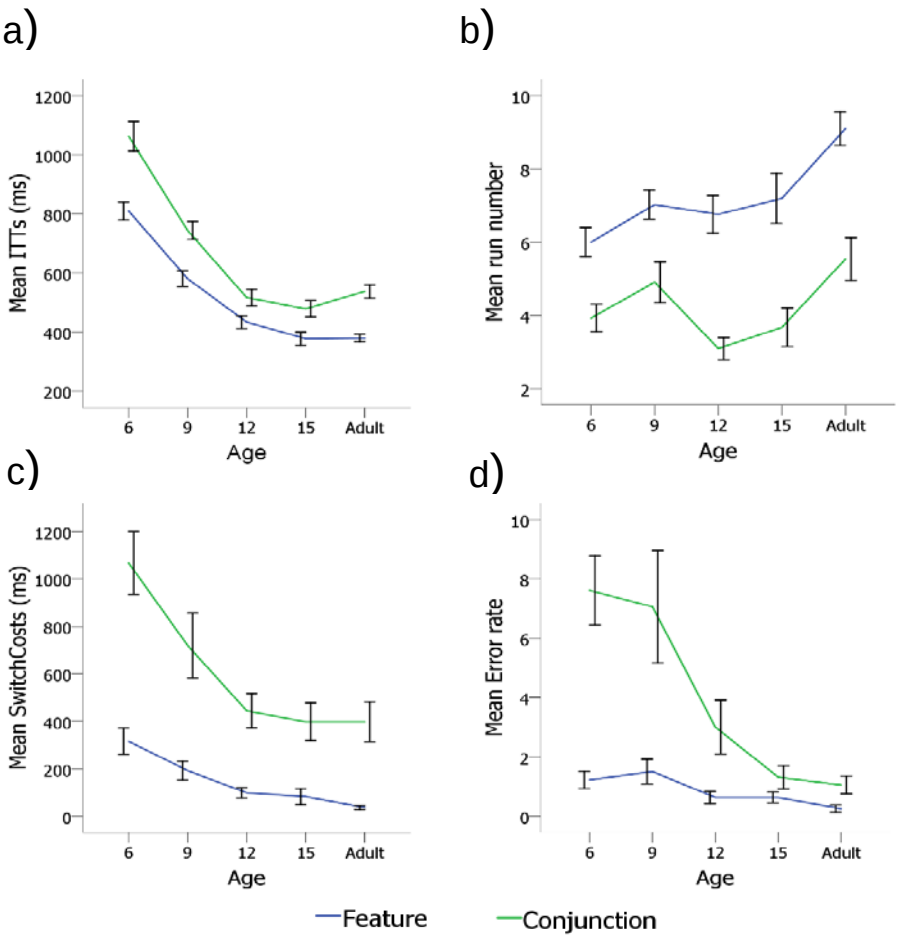

Figure 16. Differences in foraging by age and condition. **(A)** Mean inter-target times (ITTs) per age group. **(B)** Mean number of runs on a trial per age group. **(C)** Mean switch cost per age group. **(D)** Mean error rates in a trial per age group. Blue lines represent feature foraging, and green lines represent conjunction foraging. Error bars show ± 1 standard error of the mean.

in both foraging conditions, followed by the 9-year-olds, but there was no significant difference between the foraging speeds of the other age groups (all *p*s > .939). The 6-and 9-year-olds also made more errors than the other groups during conjunction foraging.

Table 7. Mean performance of each age group in all foraging measures.

	ITTs (ms)	Switch costs (ms)	Runs (n)	Errors (n)
Feature foraging				
6 years	809.47$_{2**3**4**5**}$	315.54	6.00$_{5**}$	1.22
9 years	580.26$_{1**3*4**5**}$	191.87	7.02	1.50
12 years	433.54$_{1**2*}$	98.34	6.76$_{5*}$	0.63
15 years	377.69$_{1**2**}$	82.15	7.19	0.63
Adults	379.54$_{1**2**}$	36.47	9.1$_{1**3*}$	0.25
Conjunction foraging				
6 years	1062.72$_{2**3**4**5**}$	1067.66$_{3**4**5**}$	3.92	7.61$_{3**4**5**}$
9 years	743.48$_{1**3**4**5**}$	719.30	4.91	7.06$_{3**4**5**}$
12 years	516.66$_{1**2**}$	444.21$_{1**}$	3.09$_{5*}$	3.00$_{1**2**}$
15 years	479.05$_{1**2**}$	397.73$_{1**}$	3.67	1.31$_{1**2**}$
Adults	537.44$_{1**2**}$	397.87$_{1**}$	5.54$_{3*}$	1.05$_{1**2**}$

Note: Subscripts indicate significant differences between groups according to Tukey HSD post hoc comparison. 1 = 6-year-old, 2 = 9-year-old, 3 = 12-year-old, 4 = 15-year-old, 5 = adult. *= $p < 0.05$, ** = $p < 0.001$.

The switch costs of 6-year-olds were also significantly higher than the switch costs for the older observers during conjunction foraging, with the difference between 6- and 9-year-olds being close to significance ($p = .057$). When looking at these three measures, it seems that foraging performance continues to improve up until late childhood, when it starts to level off. The only measure that con tinues to show improvement up until adulthood is the number of runs. During feature foraging, adult participants foraged in significantly more runs per trial than both 6- and 12-year-old observers.

4.4.2 Foraging and executive functions

Due to multicollinearity of the independent measures, PLS–SEM was used to explore the relationship between executive functions and foraging. The dependent measures selected for the model were the switch costs and error rates of the conjunction trials, the number of runs of the feature trials, and the mean ITTs of each participant, collapsed over the two foraging conditions. Running the model with ITTs in feature and conjunction trials separately resulted in outer path loadings of .953 and .957, respectively, and did not affect the inner loadings, reliability, or validity of the model. We decided to collapse those two measures to simplify the model. The rest of the foraging measures were excluded because of their truncated range. Table 8 shows summary statistics of the executive function measures that were used in the model. Because both executive functions and foraging performance covary with age, a measure of age was added to the model to prevent confounding.

Table 8. Summary statistics (mean and standard deviation) of executive functioning measures divided by age group.

	Inhibition		Attentional flexibility		Working memory		Problem solving	
	M (n)	sd (n)	M (ms)	sd (ms)	M (ms)	sd (ms)	M (n)	sd (n)
6 y	5.44	3.79	618.61	273.22	2323.44	708.25	54.22	20.62
9 y	3.69	3.55	560.63	176.84	2172.50	657.06	41.19	16.97
12 y	3.13	2.36	335.72	174.92	1780.75	609.13	30.88	11.19
15 y	1.63	1.15	260.13	82.07	1884.63	392.28	18.63	9.63
Adult	0.95	0.95	230.40	70.03	1487.55	399.73	18.65	16.22

Note: Inhibition is measured in the mean number of false alarms. Problem solving is measured in the number of moves it took to complete the task.

4.4.2.1 Measurement model assessment

The first step in evaluating a reflective PLS–SEM model is assessing its reliability and validity. Indicators' reliability is measured with their loadings onto latent variables. Hair et al. (2019) proposed that indicator loadings lower than .708 are unreliable and should be removed from the model. The loadings of the number of runs, errors, and working memory were .595, .621, and .629, respectively. Removing only the number of runs results in adequate model reliability, so given the exploratory purposes of the model, it was decided not to remove error rates and working memory. All other indicator loadings were .729 or higher (see Fig. 17). Cronbach's alpha and composite reliability are used to assess the internal consistency reliability of the model. In exploratory models like the current one, values of .60 or higher are acceptable (Ali et al., 2018; Hair et al., 2019). Cronbach's alpha is considered to be conservative and may underestimate the true reliability of the measures, whereas composite reliability is liberal and may overestimate the reliability. Therefore, it can be assumed that true values lie somewhere between the two coefficients (Diamantopoulos, Sarstedt, Fuchs, Wilczynski, & Kaiser, 2012; Hair et al., 2019). Table 9 shows the internal consistency reliability of the PLS model. All values are >.60 and therefore acceptable for exploratory analyses. Convergent validity is measured with the average variance extracted (AVE); if it is above .50, the construct explains over half of the variance of its items (Chin, 1998; Ringle et al., 2020). In the current model, all AVE coefficients are >.50, indicating that explained variance is sufficiently high.

Table 9. Internal consistency reliability and convergent validity of the PLS-SEM model.

	Cronbach's alpha	Composite reliability	AVE
Age	1.00	1.00	1.00
Executive functions	0.743	0.842	0.578
Foraging	0.635	0.804	0.587

Note: AVE = average variance extracted

The heterotrait–monotrait (HTMT) ratio and cross-loadings of the indicators onto the latent variables were used to assess discriminant validity. The HTMT ratio measures the correlations between indicators from different latent variables and compares them with correlations of indicators loading onto the same latent variables (Henseler, Ringle, & Sarstedt, 2015). If the HTMT value is below 1, discriminant validity has been affirmed. In the current model, the HTMT value of age and executive functions is 0.74 and that of age and foraging 0.77. But the HTMT value of executive functions and foraging is 1.10, which suggests that discriminant validity is not optimal. Another way of evaluating discriminant validity is by assessing cross-loadings. When models have good discriminant validity, indicators load highly onto their intended latent variable and cross-loadings onto other latent variables are low. A rule of thumb is that, ideally, intended loadings should be >.70 and cross-loadings should be <.40 (Falk & Miller, 1992; Garson, 2016). A minimum requirement is that each indicator loads higher onto its own latent variable than onto other latent variables (Garson, 2016). Table 10 shows the loadings of indicators onto latent variables. Cross-loadings are indeed high, but the minimum requirement that each indicator should load highest onto the intended variable is nevertheless reached. All interpretations of the model will need to carry this caveat.

Table 10. Loadings of indicator variables onto latent variables.

	Age	Executive functions	Foraging
Age	**1.00**	-0.640	-0.622
Inhibition	-0.455	**0.725**	0.540
Attentional flexibility	-0. 555	**0. 831**	0. 627
Working memory	-0.453	**0.629**	0.499
Problem solving	-0.485	**0.842**	0.708
ITTs	-0.581	0.761	**0.894**
Switch costs	-0.392	0.572	**0.753**
Errors	-0.438	0.411	**0.621**

Note: Loadings onto intended latent variables are displayed in bold.

4.4.2.2 Structural model assessment

The second step of the model assessment is evaluation of the structural model, which includes measuring the path coefficients, collinearity, R^2, and the predictive power of the model (Hair et al., 2019). Table 11 displays the inner model effects. The direct effects are the path loadings seen in Fig. 17. The indirect effects show the effects of age on foraging through executive functions. The total effects are the sums of direct and indirect effects. All effects are significant (see Fig. 17). The direct effect of age on foraging decreases significantly when the effects of executive functions are taken into account. There is a considerable indirect effect of age on foraging through executive functions, which means that the age differences in Fig. 16 and Table 7 are connected to the maturation of executive functions to a large extent. Every indicator loads strongly onto the latent executive functioning variable, indicating that they all relate to foraging.

The variance inflation factor (VIF) is used to assess collinearity. If the VIF coefficient is higher than 5 (Hair et al., 2011) or a stricter 3.33 (Diamantopoulos & Siguaw, 2006), there may be a problem with collinearity. Table 12 shows that even according to the more conservative criterion, the model does not show multicollinearity between the latent variables.

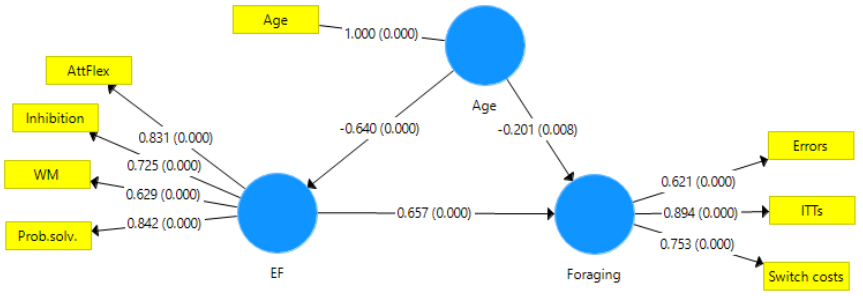

Figure 17. A partial least squares structural equation model of the relationship among age, executive functions (EF), and foraging. Numbers on arrows represent path loadings, and p values acquired by bootstrapping are shown in parentheses. AttFlex, attentional flexibility; WM, working memory; Prob.solv., problem solving; ITTs, inter-target times.

Table 11. Inner model effects.

	Direct effects	Indirect effects	Total effects
Age → Executive functions	-0.640	---	-0.640
Age → Foraging	-0.201	-0.420	-0.622
Executive functions → Foraging	0.657	---	0.657

The explained variance for the latent variables is moderately high. The Stone–Geisser Q^2 and the $Q^2_{predict}$ coefficients are acquired with blindfolding and PLSpredict cross-validation techniques, where values of .02, .15, and .35 are interpreted as weak, moderate, and strong, respectively (Cohen, 1988, Garson, 2016). With Q^2 and $Q^2_{predict}$ values between from .23 to .37, the model's predictive power is moderate to strong.

Table 12. Structural evaluation of the PLS-SEM model.

	VIF	R^2 adjusted	Q^2	$Q^2_{predict}$
Age	1.00	---	---	---
Executive functions	1.694	0.432	0.225	0.333
Foraging	1.694	0.645	0.340	0.371

Note: VIF = variance inflation factor.

To summarize, the PLS–SEM technique is adequately reliable and valid, although its discriminant validity could be higher. The main conclusions from the model are that executive functions and foraging are highly related and that the effects of age on foraging are highly connected to the maturation of executive functions. Cross-validation revealed that the predictive power of the model is moderate to strong, indicating that the same or similar results should be obtained in a new study with a different sample of participants. However, we emphasize that the cross-loadings in the model are high, so the modeling results must be interpreted with this caveat in mind. But we also note that the requirement that each indicator should load highest onto the intended variable is met (see Table 10).

4.5 Discussion

For the first time in the literature, we used a cross-sectional experimental design with foraging to investigate the development of visual attention and multiple executive functions, spanning ages from early childhood until

adulthood. We have both replicated and built on previous findings on the development of foraging abilities. In Ólafsdóttir et al. (2016), the foraging of 4- to 7-year-old children was measured and compared with adult performance. The findings suggested that the youngest participants had great difficulty in foraging for conjunctively defined targets. Many of them were unable to complete even a single conjunction trial. They foraged more slowly than adults during both feature- and conjunction-based foraging, and they refrained from switching between target types even during feature foraging. This is of great interest because it is in direct contrast to results from single-target visual search studies, which have found little or no differences between feature search of young children and adults (Gerhardstein & Rovee-Collier, 2002; Merrill & Conners, 2013; Merrill & Lookadoo, 2004). Once again, this showed how foraging tasks are far more sensitive to the dynamics of visual attention than single-target search tasks (see Kristjánsson et al., 2020, for a review). The foraging abilities of 11- and 12-year-old children, on the other hand, were similar to those of adults. The 11- and 12-year-olds foraged as quickly, their switch costs were the same, and they completed trials in as many runs as adult participants (Ólafsdóttir et al., 2019).

In the current study, we found improvements in all measured aspects of foraging performance up until 12 years of age, when it levels off into performance comparable to adults on three of four measures. More specifically, ITTs and switch costs gradually decrease until 12 years, when participants have reached adult levels of both foraging speed and the cost of switching, whereas there is a distinct fall in error rates of conjunction foraging trials between 9 and 12 years. The 9-year-old participants make as many errors as 6-year-olds, but they forage faster both within runs and while switching. The number of runs during feature foraging continues to increase into adulthood, although other measures stabilized after 12 years, which means that increased switching between target types does not result in slowing down or more errors, and the lack of decline in switch costs as the number of runs go up indicates that it is not the cost of switching that affects decisions about switches between target types but rather some sort of strategizing or reasoning about how to best complete the trials. These results were obtained even though the number of items on the screen was only half of what was displayed in previous studies (Ólafsdóttir et al., 2016, 2019), indicating that these age effects emerge even in relatively easy tasks.

4.5.1 Executive functions and foraging

There is some prior evidence for a connection between foraging and executive functions. Previous research with 4- to 7-year-old children, 11- and 12-year-old children, and adults has shown that foraging speed and switch costs (Ólafsdóttir et al., 2016, 2019), but not the number of runs (Jóhannesson et al., 2017; Ólafsdóttir et al., 2016, 2019), are connected with attentional flexibility and working memory. A study on patch-leaving behavior during foraging for information showed that older adults with greater executive control were able to adjust their patch-leaving decisions to maximize information gain, whereas seniors with lower executive control abilities tended to persist in the same patch even though little information was left to gain from it (Chin et al., 2015). In addition, an archaeological study has claimed that the reason humans started to forage for food was enhanced working memory capacity (Wynn & Coolidge, 2017).

Here, we continued this inquiry into whether, and then how, executive functions influence foraging. We added a measure of problem solving and used a simple response inhibition measure. Previous studies from our lab (Jóhannesson et al., 2017; Ólafsdóttir et al., 2019) had used a complex inhibition task, where observers needed to remember an arbitrary rule, inhibit a prepotent response, and produce an alternative response. These types of inhibition tasks are taxing for working memory, and therefore the task confounds these two executive functions (Best & Miller, 2010; Garon et al., 2008). In the go/no-go task used in the current study, there is a simple rule to remember, but no alternative response is required, only inhibition. Therefore, this task should be a purer measure of inhibition than the previously used tasks.

Due to multicollinearity of the executive functioning measures and a relatively small sample size, PLS–SEM was conducted to get an insight into the relationship between executive functions and foraging. The model's reliability and convergent validity were good, but the HTMT ratio between executive functions and foraging was relatively high. That means that the discriminant validity of the model might not be adequate, which indicates that there may be overlap in the executive functioning and foraging measurements. The path loadings of executive functions onto foraging are indeed high, which suggests that the two constructs are highly related. Given the strong connection between executive functions and foraging found in the current study, it is even possible that foraging tasks could be used as a proxy for executive functional abilities. Because this study is intended to be exploratory

and the minimum requirement is that no indicator cross-loadings are higher than the loading onto the intended latent variable (Garson, 2016), we carried on with the analysis, but all interpretations carry this caveat.

There is a large body of research that demonstrates the importance of various conceptions of attention for children's healthy functioning, including academic performance (see, e.g., Polderman et al., 2010; Rhoades et al., 2011; Steinmayr et al., 2010). As such, understanding how different aspects of attention develop, and how they relate to other (even overlapping) constructs such as executive functions, helps us to better understand how and when children attain this important ability. In addition, studying how executive functions relate to foraging gives us insights into our cognitive functions as we orient our attention through the environment.

The PLS–SEM of the effect of age and executive functions on foraging can be seen in Fig. 17. When the effects of executive functions are taken into account, the direct effect of age on foraging diminishes significantly. There is still a considerable indirect effect of age on foraging through executive functions, but this means that the age differences seen in Fig. 16 and Table 7 are related to a considerable extent to the maturation of executive functions. All indicators load relatively highly onto the latent executive functioning variable, so they all seem to affect foraging to some degree. Interestingly, the loading of inhibition onto the latent variable is high, which suggests that inhibition is related to foraging. This relationship has not been found in previous studies, but as previouslymentioned, a complex inhibition task has been used up until now, where a simple go/no-go task was administered as an inhibition measure.

Although the current model shows that there is a strong connection between executive functions and foraging and that this connection correlates highly with age differences in foraging abilities, it does not reveal how the executive functions of each age group relate to foraging. There is some evidence that this relationship changes throughout development. Ólafsdóttir et al. (2019) found that the relationship between executive functions and foraging differed between age groups even though there were no age differences in foraging performance. Multiple linear regression revealed that ITTs were related to attentional flexibility in children but to working memory in adults, and switch costs were related to attentional flexibility and working memory in children, but no connection was found between switch costs and executive functions in adults.

Different executive functioning components develop at different rates (Klenberg et al., 2001; Lee et al., 2013), which can affect how executive functions relate to other constructs. Senn et al. (2004) measured inhibition, attentional flexibility, working memory, and problem solving in children aged 2 to 6 years. They found that for children younger than 4 years inhibition predicted performance on the Tower of London task, but in children aged 4 to 6 years performance was now predicted by working memory capacity. The correlation between inhibition and working memory was also moderate in the younger age group but had disappeared in the older children. The same principle might explain the differential connections between foraging and executive functioning performance found in Ólafsdóttir et al. (2019). Therefore, it is an important next step to tease apart the effects of the different subcomponents of executive functions on visual attention tasks throughout development.

4.5.2 Conclusions and future directions

The foraging performance of children aged 6 to 12 years improves on all measures included in this study, and by 12 years children have reached adult levels of performance. Foraging abilities have a strong connection with executive functions; there is a small direct effect of age on foraging, but there is a considerable indirect effect through executive functions. Because different components of executive functions develop at a different rate, and their relationship with each other and other constructs changes throughout development, the next step in discovering how executive functions affect foraging abilities should be to analyze this relationship separately for different age groups. Furthermore, a longitudinal study on this topic would help to confirm how these capabilities and the connection between them develop over time.

5 Paper III

The following chapter is a manuscript submitted for review in Attention, Perception, & Psychophysics under the name: The development of foraging organization. The authors are Ólafsdóttir, I. M., Gestsdóttir, S. & Kristjánsson, Á. Figure numbers, references and some formatting has been changed from the published paper for continuity with the thesis as a whole. Any references to content within this chapter should be as follows:

Ólafsdóttir, I. M., Gestsdóttir, S., & Kristjánsson, Á. (submitted). The development of foraging organization. *Attention, Perception, & Psychophysics.*

5.1 Abstract

Foraging tasks involve visual search where multiple targets must be found within a single display. The targets can be of one or more types, typically surrounded by numerous distractors. Visual attention has traditionally been studied with single target search tasks but adding more targets to the search display results in several additional measures of interest, such as how attention is oriented to different features and locations over time. We measured foraging among five age groups: Children in grades 1, 4, 7, and 10, as well as adults, using both feature and conjunction foraging tasks, with two target types per task. We assessed participants' foraging organization, or systematicity of selecting all the targets within the foraging display, on four measures: Intertarget distance, number of intersections, best-r, and the percentage above optimal path length (PAO). We found that foraging organization increases with age, for both simple feature-based foraging and more complex foraging for targets defined by feature conjunctions, and that feature foraging was more organized than conjunction foraging. Separate analyses for different target types indicated that children's, and to some extent adults', conjunction foraging consisted of two relatively organized foraging paths through the display where one target type is exhaustively selected before the other target type is selected. Lastly, we found that the development of foraging organization is closely related to the development of other foraging measures. Our results suggest that measuring foraging organization is a promising avenue for further research into the development of visual orienting.

5.2 Introduction

Picture a child eating a sugary cereal filled with marshmallows. Instead of eating it by the spoonful, the child sifts through the bowl, picking out the marshmallows from the cereal. This is an example of a foraging task. Foraging tasks involve visual search where multiple targets must be found within a single display. The targets can be of one or more types and are usually surrounded by numerous distractors of one or more types. While visual attention has traditionally been studied with single target search tasks (see e.g. Huang & Pashler, 2005; Maljkovic & Nakayama, 1994, 1996; Najemnic & Geisler, 2005; Pashler, 1987; Wolfe, 2010; see Kristjánsson, 2015 for a critical review) foraging studies have been gaining more interest in the last decade as they may provide a more intricate picture of how we orient in the visual world (see e.g. Cain et al., 2012; Kristjánsson et al., 2014; Ólafsdóttir et al., 2019, 2020; Thornton et al., 2019; Wolfe, 2013; Wolfe et al., 2019; Zhang et al., 2017; see Kristjánsson et al., 2019 for review). These studies have revealed that when observers forage for targets of different types, the conspicuousness of the search item is crucial. If the items are clearly visible and easily discerned from the distractors, subjects tend to readily switch between target categories as they forage. On the other hand, if the target items are indistinct, or very similar to the distractors, subjects select the same target type in long runs, without switching (Bond, 1982; Dukas & Ellner, 1993).

5.2.1 The Development of Visual Attention and Single Target Search Tasks

Because foraging studies are a relatively recent development in studies of human visual attention, what is known about its the development has mostly come from studies using single target search tasks. A large body of literature has revolved around performance differences between feature and conjunction search (see e.g. Humphrey & Kramer, 1997; Scialfa & Joffe, 1998; Treisman et al., 1977; see Kristjánsson & Egeth, 2020 for review). When targets are defined by a single feature, such as color or shape, search is usually quick and effortless, regardless of the number of distractor items on the screen. However, when targets are defined by a conjunction of two or more features, such as color and shape, e.g., when observers search for a blue triangle amongst blue dots and yellow triangles, search times increase proportionately with the number of distractor items (Humphrey & Kramer, 1997; Scialfa & Joffe, 1998; Treisman et al., 1977). Studies on children‘s visual search abilities have suggested that children and infants‘ feature search is efficient and accurate (Adler & Orprecio, 2006; Gerhardstein & Rovee-Collier, 2002; Sireteanu &

Rieth, 1992). If the target item is defined by a conjunction of two or more features, however, children have great difficulty completing the task, evident from high error rates (Gerhardstein & Rovee-Collier, 2002; Lobaugh et al., 1998) and search times that increase proportionately much more than for adults as distractor number rises (Gerhardstein & Rovee-Collier, 2002; Merrill & Lookadoo, 2004; Thompson & Massaro, 1989; Trick & Enns, 1998). These results have sparked proposals that different mechanisms underlie processing of feature and conjunction-based searches. Mechanism for processing items that are defined by a single feature, and “pop-out“, are believed to be innate or develop in the first months of life, whereas conjunction search depends upon more complex cognitive mechanisms related to the prefrontal cortex, such as executive functions that develop later in life (Gerhardstein & Rovee-Collier, 2002; Merrill & Lookadoo, 2004).

5.2.2 Visual Foraging

Kristjánsson and colleagues (2014) developed a foraging task for touch screen devices, where participants are asked to find and tap on multiple target items among multiple distractors. They speculated whether run number might be manipulated with attentional load, rather than only by the conspicuousness of items. A run is defined as the consecutive selection of the same target type. If an observer switches often between target types, a trial is completed in a series of multiple short runs. If the observer refrains from switching for extended periods, a trial will be completed in few long runs (see overview in Kristjánsson et al., 2019).

To manipulate attentional load, Kristjánsson et al. (2014) made two versions of the task. In the feature foraging version, the targets were distinguishable from the distractors by color. In the conjunction foraging version, the targets differed from the distractors by a color-shape combination and could be red squares and green dots while the distractors were green squares and red dots, or vice versa. They administered those two versions of the foraging task to 16 participants and found that just as when targets are easily distinguishable, people frequently switch between target types during feature foraging. In contrast, most participants completed the conjunction foraging trials in two long runs, exhaustively foraging for one target type before switching to the other. Run behavior was therefore dependent upon attentional load, and not solely the conspicuity of the targets.

5.2.3 Foraging and Development

Ólafsdóttir et al. (2016, 2019, 2020) administered the feature and conjunction

foraging tasks to children between the ages of 4 to 15 years and compared their performance to that of adults. They found that young children are more error prone and slower foragers than older children and adults, not only during conjunction foraging, but also during feature foraging. Children appeared to reach adult levels of performance around the age of 11 or 12 years. Younger children also tended to complete feature foraging trials in fewer runs than adults, and exhibit switch costs, their target selections were slowed when they switched between target types compared to when they selected the same type of target as during the last selection. A decrease in the number of runs and higher switch costs were seen for conjunction foraging for all ages but were very small or absent in the feature foraging of older children and adults. These results suggested that young the ability to detect items defined by a single feature is not as fully developed in childhood as previously posited.

5.2.4 Organization

When more than one target is selected on each trial, several performance measures are available that are not available in single-target search tasks, such as how attention is oriented throughout the display, and how observers process and engage with more than one target type at a time. Cancellation tasks have a lot in common with foraging tasks and could even be defined as such. Subjects are asked to find and mark, or "cancel", multiple targets on a piece of paper (Woods et al., 2013) or a computer screen (Dalmaijer et al., 2015). Cancellation tasks have been extensively used in patient groups to measure hemi-spatial neglect in stroke patients (Appelros et al., 2002; Buxbaum et al., 2004; Nijboer et al., 2013; Sævarsson et al., 2008; Ten Brink et al., 2018), dementia (Fabrigoule et al., 1998; Gainotti et al., 2001), and short-term memory deficits (Dalmaijer et al., 2018; Husain & Rorden, 2003). Because of their diagnostic use, it is important to have normative data for cancellation tasks. Therefore, cancellation tasks have also been used in studies with healthy adults of different backgrounds. Some studies show no differences of cancellation performance between different age groups (Benjamins et al., 2019; Brucki & Nitrini, 2008; Saykin et al., 1995; Warren et al., 2008), while others have found a weak age effect (Byrd et al., 2004; Lowery et al., 2004). Other demographic factors, such as sex, ethnicity, and education level, do not seem to affect cancellation behavior (Benjamins et al., 2019).

Although age does not seem to have a large effect on cancellation task performance in adults, visuospatial abilities do increase from childhood into adolescence, and seem to influence visual search performance, both in terms of speed (Burggraaf et al., 2019) and accuracy (Woods et al., 2013). Woods et

al. (2013) studied the search organization of children aged 2 to 18 years, with a paper and pencil cancellation task, where 16 target items were dispersed amongst 32 distractors. They kept track of the order of target cancellations to assess how organized the children' search was. Three measures were used to estimate search organization; mean inter-target distance, the number of intersections in the search path, and the best-r. Highly organized search often involves the subject going through the display in columns or rows, going systematically from for example left to right, or top to bottom. To capture this movement pattern, Woods et al. (2013) ran a linear regression on first the x-coordinates of the target items and the order in which they were selected, and then did the same for the y-coordinates, to get the Pearson correlation coefficient (r) from both regressions. They then selected the higher coefficient, the *best-r*, to represent the level of systematicity of each trial. A high Pearson correlation coefficient of the x-coordinates and selection number would mean that the subject systematically moved from left to right, or right to left, whereas a high Pearson correlation coefficient of the y-coordinates would mean a systematic cancelling pattern in rows from top to bottom, or bottom to top. They found that as the children grew older, the mean inter-target distance shortened, the number of intersections went down, and the best-r became higher. Additionally, they found that best-r was connected with the number of errors in a conjunction search task, but no connection was found with feature search.

Another way of operationalizing foraging organization involves the so-called travelling salesman problem (TSP) where the optimal path through the display, that is the shortest possible path through every single target item, is calculated. It is then possible to measure whether, and by how much, participants surpass the length of this optimal path length. Wiener et al. (2007) had participants navigate between 25 differently marked cardboard pillars in an experimental room, aiming for the shortest possible path between a set of up to 9 different items. They found that average surpassing of the optimal path length was just over 5%, and for the most complex routes, the percentage above optimal (PAO) was on average less than 10%. Furthermore, they found that when the target locations were clearly marked, thus diminishing mental load, participants' performance improved even further. Similar studies have been carried out in visual tasks where participants try to connect the dots in as short a path as possible, using paper and pencil (MacGregor & Ormerod, 1996, 1999), and computerized tasks (Graham et al., 2000; Vickers et al. 2003). The percentage above optimal path length in those studies ranged from 0% for the simplest tasks up to 10% for the most complex tasks.

5.2.5 The Current Study

Few studies have investigated children's organization abilities as they search for multiple targets, even though such abilities may explain to some extent the age effects found in cross-sectional studies of visual search (see e.g. Burggraaf et al., 2019; Woods et al., 2013). Here, we compare the foraging organization of five age groups, ranging from 1st graders to adults, administering both feature and conjunction foraging tasks. We use four measures of organizational abilities: The mean intertarget distance, the number of intersections, the best-r, and the percent above the optimal path length through the foraging display (PAO). We hypothesize that in line with results from Woods et al. (2013), organizational abilities will improve into adulthood, and that they will be connected with other aspects of foraging performance, in both the feature and conjunction foraging tasks. In addition, we expect that the feature foraging task will be completed in a more organized manner than the conjunction task, as the task requires less effort, and mental load affects path length (see Wiener et al., 2007).

5.3 Method

5.3.1 Participants

A total of 66 children and 23 adults participated in the experiment. The children were divided into four age groups, three school years apart from each other (see Table 13). Data from three adult participants was excluded due to color blindness. All remaining participants had normal or corrected to normal eyesight.

Table 13. Participants.

Age group	N	Mean age (years)	Age span (years)	Sd (years)	Gender
First grade	18	6.24	5.84-6.69	0.30	10 girls/8 boys
Fourth grade	16	9.44	9.06-9.78	0.22	11 girls/5 boys
Seventh grade	16	12.29	11.92-12.78	0.27	11 girls/5 boys
Tenth grade	16	15.42	14.93-15.81	0.28	12 girls/4 boys
Adult	20	25.55	21.88-48.63	6.03	12 female/8 male

The children attended two different schools in the same school district in Reykjavik. Consent forms were sent home with all the children for their parents to sign, along with further information about the study. Children in grades 7 and

10 were asked to sign the consent forms as well as their parents, but verbal assent was obtained from younger participants. No compensation was offered to the children for their participation. The adult participants were students in an undergraduate class in psychology. They were offered class credit for participating in the study.

All aspects of the experiment were reviewed and approved by the data protection authority of Iceland, the Icelandic National Bioethics Committee, (project number VSN-18-055) and permission was granted by the Reykjavik Department of Education and Youth, as well as school administrations from both schools.

5.3.2 Equipment

The task was presented on an iPad 2 with screen dimensions of 20 × 15 cm and an effective resolution of 1024 × 768 pixels. It was placed in landscape mode on a table in front of participants, with approximately 50 cm viewing distance. Stimulus presentation and response collection were carried out with a custom iPad application written in Swift using Xcode.

5.3.3 Stimuli

The display consisted of 40 stimuli on a black background, 20 targets and 20 distractors. In the feature foraging condition, the stimuli were discs of four different colors, blue, yellow, green, and red. The targets were either the green and red dots and the blue and yellow dots distractors, or vice versa. In the conjunction foraging condition, the stimuli were red and green discs and squares (see Figure 18). The targets were either the red disks and green squares and the distractors the green disks and red squares or vice versa. Their diameter was 20 pixels (approximately 0.46° visual angle). They were randomly distributed on a non-visible 10 x 8 grid and offset from the edge of the screen by 100 x 150 pixels. The viewing area was therefore 12 x 15 cm (approximately 13.7 x 17.1°). The position of each item within the grid was randomized by adding a random vertical and horizontal offset. Gaps between columns and rows ensured that items never occlude or approach one another. The location of the targets and distractors was randomly generated from trial to trial.

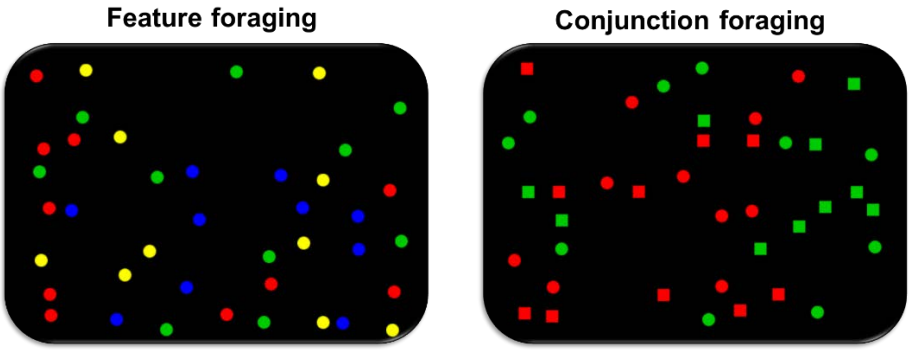

Figure 18. Screenshots of the foraging task. Feature foraging is shown on the left, conjunction foraging on the right.

5.3.4 Procedure

The experiment was run in a quiet room with normal illumination. The children were visited at school while adult observers were tested in a lab at the University of Iceland. Observers were required to fully complete ten error-free feature and ten error-free conjunction foraging trials, as well as a few tasks that were administered for the purpose of a different study (see Ólafsdóttir et al., 2020). The first and fourth graders finished the foraging task in a 20-25-minute session and the other tasks in a different session. The older children and adults finished all tasks in a single 40-50-minute session. The foraging task constituted around 15-20 minutes of the session. The first trial of each foraging condition was regarded as a practice trial and the remaining nine constituted the experiment itself. Observers were instructed to use the index finger of their dominant hand to tap all targets as quickly as they could and avoid tapping distractor items. They were informed that they could take a break between any two trials. On the feature foraging trials, the targets were red and green discs and the distractors blue and yellow discs for half of the observers, and vice versa for the other half. On the conjunction foraging trials the targets were red discs and green squares, and the distractors were green discs and red squares for half of the observers, and the reverse applied to the other half. The order of foraging conditions as well as target/distractor colors were counterbalanced across each age group.

Each trial was started by tapping anywhere on the screen. The targets disappeared upon being tapped. When every target in the display had disappeared, a smiley face appeared in the middle of the screen along with

information about how many trials had been completed and the total time it had taken to complete the previous trial. If a distractor item was tapped, an error message appeared and the trial was restarted, with a new item positions generated randomly.

5.3.5 Data Analysis

The first fully completed trial of each foraging condition was treated as a practice trial and removed from the dataset, along with all error trials. The organizational measures included best-r, intertarget distance, the number of intersections, and the percentage of path length surpassing the optimal foraging path throughout the display (percentage above optimal, PAO).

Best-r is a measure of the overall path structure or the systematicity of the foraging path of each trial. People typically forage in a systematic way in a static foraging display, for example going through it in columns or rows (Dalmaijer et al., 2015; Kristjánsson et al., 2019; T. Kristjánsson et al., 2020b; Mark et al., 2004; Woods et al., 2013). Figure 19 shows examples of structured and unstructured foraging paths through a display of 40 red and green target items among 40 blue and yellow distractors.

The best-r is found by calculating the Pearson correlation coefficient (r) from separate linear regressions of the x and y coordinates of the targets, relative to the order in which they are selected. The higher r-value (out of the x- or y-regressions) constitutes the best-r for a respective trial. It is important to note that it is possible to have a highly organized path structure which yields a low best-r value, such as going in a circle around the display or back and forwards in an L shaped path. While such strategies are hard to deal with statistically, they would presumably not affect our other organizational measures to any great extent, yielding low intertarget distances, few intersections, and a low surpassing of the optimal path length.

Intertarget distance is the mean Euclidean distance between consecutively selected targets, measured in pixels here, and intersections constitute the number of times the foraging path intersects itself on each trial. Well organized foraging should constitute moving to the most proximal target, resulting in short intertarget distances and a minimal amount of revisiting already covered sections of the display, minimizing the number of intersections (see Figure 19).

We calculated the optimal foraging path through each display by modifying the OR-Tools 7.2 code (Perron & Furnon, 2019), reiterating the code for each possible starting point in the display. The optimal path is defined as the shortest path throughout the display starting from the first target selected on each trial,

but with no predefined endpoint. The percentage above the optimal foraging path (PAO) on each trial was then calculated by dividing the length of the travelled path by the optimal length, subtracting 1, and multiplying by 100 (see Wiener et al., 2007, for similar methods).

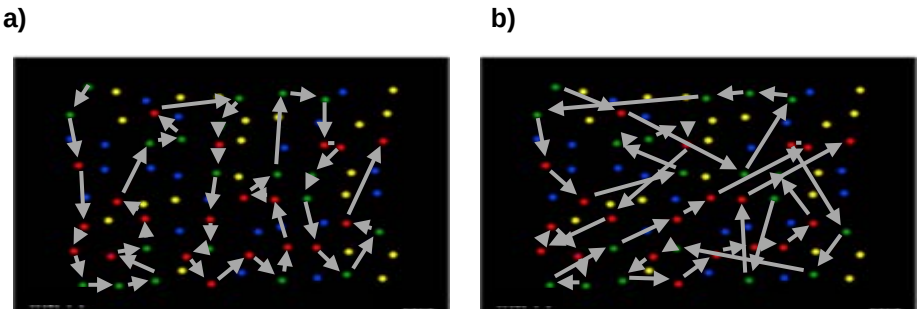

Figure 19. Examples of structured (**panel a**) and unstructured (**panel b**) foraging paths with the same start and end points. **Panel a** shows a trial where an observer searches systematically through columns of the foraging display. In this example, the overall path is consistently moving rightwards, which would result in a high r-value for the x-axis. **Panel b** shows an unstructured path which should result in a low r-value on both the x and y- axes.

Age differences in foraging organization were assessed with repeated measures ANOVAS with foraging condition as a within-subject and age group as a between-subject factor and the organization measures as dependent variables. A Greenhouse-Geisser correction was used to correct for sphericity.

Lastly, to see how foraging organization relates to other foraging measures, a series of single linear regressions were conducted. To correct for multiple comparisons, the *p*-value of each regression was multiplied by the number of comparisons. Analyses were carried out with SPSS, JASP and R.

5.4 Results

The aim of this study was to investigate age differences in foraging organization, in other words, whether the systematicity of the movement pattern through the foraging path would increase with age. There are two foraging paradigms in this study, feature and conjunction foraging. The conjunction foraging task is more demanding and places a higher mental load onto the observers completing the task. Another aim was to find out whether there were differences in organization between these two paradigms, and if so,

whether these differences were due to mental load. Lastly, the connection between organization and other aspects of foraging was measured.

5.4.1 Age differences in foraging organization

Figure 20 shows that the foraging paths were more structured for feature than conjunction foraging for all age groups, and older participants went through the foraging displays in a more structured way than the younger participants. A repeated measures ANOVA with group as a between subjects factor revealed a significant difference of the best r between feature and conjunction foraging, $F(1, 81) = 104.36$, $p < 0.001$, $\eta_p^2 = 0.563$ and a significant age difference, $F(4, 81) = 7.25$, $p < 0.001$, $\eta_p^2 = 0.264$, but no interaction between foraging task and age ($p = 0.134$, $\eta_p^2 = 0.082$).

A Holm corrected post hoc comparison revealed a significant difference in best-r for feature foraging trials between adults and 1st graders, $t = -4.49$, $p < 0.001$, Cohen's d = -0.484, adults and 4th graders $t = -3.44$, $p = 0.021$, Cohen's d = -0.371, and adults and 7th graders $t = -3.82$, $p = 0.006$, Cohen's d = -0.412. A significant difference in best-r for conjunction foraging was found between 7th graders and adults, $t = -3.67$, $p = 0.010$, Cohen's d = -0.395.

Figure 20 shows the mean intertarget distance for each age group in panel b. The intertarget distance decreased with participants' age, and for each age group the distance was larger for conjunction foraging. A repeated measures ANOVA revealed a significant difference in intertarget distance between feature and conjunction foraging trials, $F(1, 81) = 138.41$, $p < 0.001$, $\eta_p^2 = 0.631$ and a significant age difference, $F(4, 81) = 8.11$, $p < 0.001$, $\eta_p^2 = 0.286$, but no interaction between foraging task and age ($p = 0.986$, $\eta_p^2 = 0.004$). Holm corrected post hoc comparisons reveal significant differences between 1st graders and adults in both feature and conjunction foraging, $t = 4.54$, $p < 0.001$, Cohen's d = 0.490, and $t = 4.48$, $p < 0.001$, Cohen's d = 0.483, respectively.

There was also a significant age difference in the number of intersections, $F(4, 81) = 15.67$, $p = 0.011$, $\eta_p^2 = 0.148$ but no difference between the two foraging conditions and no interaction between age and foraging task (ps = 0.536 and 0.371, respectively; see Figure 20, panel c). Holm corrected post hoc tests show significant differences between 1st and 7th graders, $t = 3.37$, $p = 0.043$, Cohen's d = 0.363, and 1st and 10th graders, $t = 3.66$, $p = 0.016$, Cohen's d = 0.395 on conjunction foraging trials. No significant age differences were found in the feature task (all ps = 1.00).

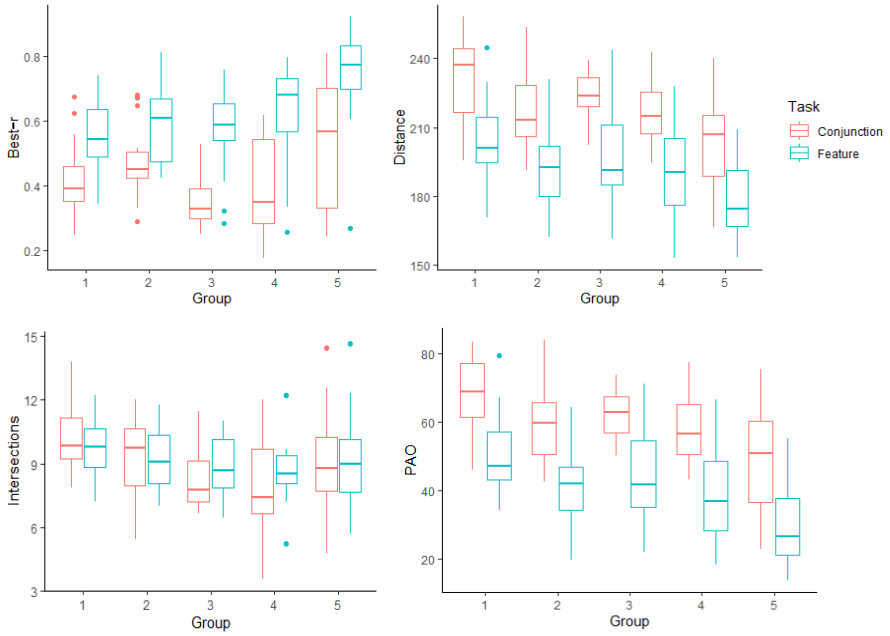

Figure 20. The four organizational measures shown by age and foraging task. **Panel a** shows the distribution of the best-r of each age group in feature and conjunction foraging. Best-r is a measure of the systematicity of the movement pattern in each trial, the higher the best-r, the more systematical the path through the target items. **Panel b** shows intertarget distance in pixels in each foraging task divided between age groups. **Panel c** shows the number of intersections per trial and **panel d** the surpassing of the optimal path through the display in percentages. PAO = Percent above optimal. Groups: 1 = 1st grade, 2 = 4th grade, 3 = 7th grade, 4 = 10th grade, 5 = adults.

A repeated measures ANOVA with group as a between subjects factor revealed a significant difference in the PAO between feature and conjunction foraging, $F(1, 81) = 159.72$, $p < 0.001$, $\eta_p^2 = 0.663$ and a significant age difference, $F(4, 81) = 8.48$, $p < 0.001$, $\eta_p^2 = 0.295$, but no interaction between foraging task and age ($p = 0.971$, $\eta_p^2 = 0.006$). Panel d of Figure 20 shows how the PAO decreased with each age group, and how it was smaller for feature than conjunction foraging trials for all age groups. Holm corrected post hoc comparisons showed significant differences of PAO between 1st graders and adults, $t = 5.04$, $p < 0.001$, Cohen's d = 0.544, and 7th graders and adults, $t = 3.29$, $p = 0.032$, Cohen's d = 0.354, in the feature foraging task, and between 1st graders and adults in the conjunction foraging task, $t = 4.31$, $p = 0.001$, Cohen's d = 0.465.

5.4.2 Conjunction foraging – two trials per display?

Three out of four organizational measures showed more organized feature than conjunction foraging. Previous research using the foraging task developed by Kristjánsson et al. (2014) has shown that most people complete the conjunction foraging task in two runs, that is, they exhaustively forage for all targets of one type, before turning to the other type (see e.g. Kristjánsson et al., 2014; T. Kristjánsson et al., 2020a; Jóhannesson et al. 2016; Ólafsdóttir et al., 2019; but see also T. Kristjánsson et al., 2018, for some exceptions). The current task is a simplified version of the Kristjánsson et al. (2014) task, with 40 rather than 80 items on the screen. Regardless, all age groups completed the conjunction foraging trials in fewer runs than the feature foraging trials, and a large percentage of conjunction trials were completed in just two runs (see Table 14). It is therefore possible that observers effectively treated the conjunction foraging task as two consecutive foraging tasks displayed on the same screen, where participants complete one task at a time in a highly organized manner. If that is the case, it is problematic to treat the two resulting foraging paths per trial as a single path. We tested this by calculating the PAO and best-r separately for each target type per trial. We added the resulting two PAOs per trial together and found the mean of the two best-r's per trial and compared them to the overall conjunction and feature trial results (see Figure 21).

Table 14. Descriptive statistics for run numbers.

Group	Task	Mean	Sd	Percent
1st grade	F	6.00	2.75	13.0
4th grade	F	6.99	2.69	5.6
7th grade	F	6.77	3.21	13.2
10th grade	F	7.19	3.54	18.8
Adult	F	9.10	2.93	5.0
1st grade	C	3.83	2.28	43.2
4th grade	C	4.79	3.52	34.0
7th grade	C	3.01	1.91	66.7
10th grade	C	3.65	2.57	59.7
Adult	C	5.55	3.14	32.2

Note: F = feature foraging, C = conjunction foraging. Percent = percentage of trials completed in two runs.

A repeated measures ANOVA showed a significant difference between the PAO of overall feature, overall conjunction and separated conjunction foraging, $F(1.89, 153.16) = 92.26$, $p < 0.001$, $\eta_p^2 = 0.53$, as well as age differences, $F(4, 81) = 7.98$, $p < 0.001$, $\eta_p^2 = 0.28$, and a significant interaction between PAO and age, $F(7.56, 153.16) = 2.43$, $p = 0.019$, $\eta_p^2 = 0.11$. Post hoc analyses revealed a significant difference between the overall feature and conjunction tasks for every age group, all ps < 0.001, all Cohen's ds > 0.539. There was also a significant difference between overall and separated conjunction trials for 1st graders: $t = 5.27$, $p < 0.001$, Cohen's d = 0.568, 4th graders: $t = 4.29$, $p = 0.002$, Cohen's d = 0.463, 7th graders: $t = 7.11$, $p = < 0.001$, Cohen's d = 0.767, and 10th graders: $t = 5.83$, $p = < 0.001$, Cohen's d = 0.628, but not for adults, $p = 0.214$, Cohen's d = 0.317. Lastly, there was a significant difference between feature foraging trials and the conjunction foraging trials with separated target types in the adult group, $t = -3.48$, , $p = 0.042$, Cohen's d = -0.376, but no other group.

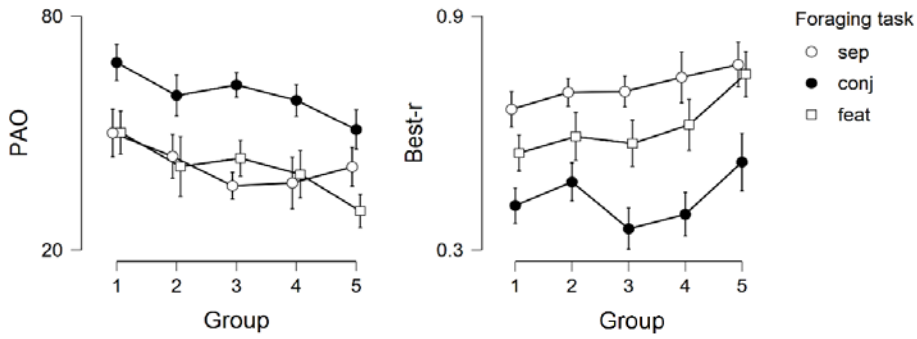

Figure 21. The difference between the PAO (**panel a**) and best-r (**panel b**) for overall feature foraging trials (white squares), overall conjunction foraging trials (black dots) and conjunction foraging trials where organization was calculated separately between target 1 and 2 and then added together (white dots). Groups: 1 = 1st grade, 2 = 4th grade, 3 = 7th grade, 4 = 10th grade, 5 = adults.

Separating target types had a similar effect on the best-r, there was a significant difference between foraging tasks, $F(1.94, 157.27) = 150.27$, $p > 0.001$, $\eta_p^2 = 0.650$, age groups, $F(4, 81) = 10.38$, $p > 0.001$, $\eta_p^2 = 0.339$, and a significant interaction between task and age, $F(7.77, 157.27) = 2.06$, $p = 0.045$, $\eta_p^2 = 0.092$. Post hoc analyses revealed a significant difference between overall feature and conjunction foraging for all age groups except 4th graders,

all significant *p*s < 0.016, Cohen's d = -0.400, -0.611, -0.640, and -0.705 for 1st, 7th and 10th graders, and adults, respectively, $p = 0.127$, Cohen's d = -0.325 for 4th graders. There was a significant difference between overall and separated conjunction trials for all age groups, all *p*s < 0.001, Cohen's d ranges from -0.642 to -0.982. A significant difference was found between the overall feature and separated conjunction trials for the 7th graders, $p = 0.036$, Cohen's d = -0. 372, but not for any other age group, all *p*s > 0.089.

5.4.3 Is foraging organization connected to any other foraging measures?

Table 15 shows the mean and standard deviation of various foraging measures (for extensive analyses of these measures, see Ólafsdóttir et al. 2020). The intertarget times (ITTs) are a measure of foraging speed, or the time that passes between each tap on a target. Switch costs are the differences of intertarget times between selecting the same target as previously or switching between target types. As can be seen in Table 15, switching between target types usually involves slower ITTs than repeatedly selecting the same target type especially in the conjunction foraging task, but the youngest participants also slow down considerably when switching between target types in the feature foraging task. Runs are a measure of how often participants switch between target types. One run is defined as a repeated selection of the same target type. When a participant switches between target types a new run is started. Therefore, the number of runs per trial constitutes the number of switches + 1 (the first run, which is not counted as a switch). Errors is the mean number of errors that are made as observers attempt to finish 10 trials.

Woods et al. (2013) studied search organization with a paper and pencil cancellation task and showed that organizational abilities are connected to accuracy in conjunction search, concluding that children's lack of ability to plan and execute organized search affected their conjunction search abilities. The paper and pencil task used in their study can be defined as a foraging task, as the participants were instructed to find 16 target items embedded within a number of distractors. In an attempt to replicate and build upon their findings, we assessed whether foraging organization is connected to other foraging measures with a series of single linear regressions (see Tables 16 and 17). As Table 16 shows, the error rates are not connected to any organizational measure, but three out of the four organizational measures are connected with other foraging measures, such as foraging speed (ITTs), how often participants switch between target types (runs) and the cost of switching.

Table 15. Mean and SD of each age group for various foraging measures.

Feature foraging

	ITTs (ms)		Switch costs (ms)		Runs		Errors	
Group	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	809.47	130.18	315.54	231.78	6.00	1.68	1.22	1.22
2	580.26	106.53	191.87	158.81	7.02	1.60	1.50	1.67
3	433.54	84.94	98.34	84.56	6.76	2.06	0.63	0.81
4	377.69	88.29	82.15	137.70	7.19	2.76	0.63	0.72
5	377.93	57.08	36.61	40.79	9.09	2.11	0.26	0.56

Conjunction foraging

	ITTs		Switch costs		Runs		Errors	
Group	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	1062.72	210.85	1067.66	562.68	3.92	1.58	7.61	4.94
2	743.48	123.09	719.30	546.91	4.91	2.24	7.06	7.58
3	516.66	112.47	444.21	292.62	3.09	1.20	3.00	3.63
4	479.05	111.99	397.73	317.60	3.67	2.10	1.31	1.54
5	535.41	106.56	404.90	385.72	5.51	2.69	1.11	1.37

We did not replicate Woods et al.'s finding about the connection between error rates and conjunction search organization (see Table 17). But the other three foraging measures were connected with best-r, intertarget distance, and PAO, but not the number of intersections.

Table 16. Linear regressions on foraging organization and other measures in the feature foraging task.

		B	t	p_{corr}	Adj. R^2
Best-r	Runs	0.83	13.66	**< 0.001**	0.686
	ITTs	-0.31	-3.03	*0.05*	0.088
	Switch costs	-0.54	-5.87	**< 0.001**	0.282
	Errors	-0.04	-0.37	> 0.71	-0.010
Target distance	Runs	-0.81	-12.77	**< 0.001**	0.656
	ITTs	0.35	3.47	**0.01**	0.115
	Switch costs	0.61	7.03	**< 0.001**	0.363
	Errors	0.02	0.19	> 0.85	-0.011
Intersections	Runs	0.12	1.06	> 0.29	0.001
	ITTs	0.17	1.59	> 0.12	0.018
	Switch costs	0.09	0.85	> 0.40	-0.003
	Errors	0.06	0.52	> 0.60	-0.009
PAO	Runs	-0.82	-13.29	**< 0.001**	0.674
	ITTs	0.39	3.91	**0.003**	0.144
	Switch costs	0.60	6.93	**< 0.001**	0.356
	Errors	0.05	0.41	> 0.68	-0.010

Note: B = Standardized β, p_{corr} = p values corrected for multiple comparisons. PAO = percentage above optimal. Significant *p*-values are displayed in bold. A *p*-value approaching significance is shown in italics. All DF = 84.

Table 17. Linear regressions on foraging organization and other measures in the conjunction foraging task.

		B	t	p_{corr}	Adj. R^2
Best-r	Runs	0.81	12.72	**< 0.001**	0.654
	ITTs	0.05	0.45	> 0.65	-0.009
	Switch costs	-0.34	3.33	**0.020**	0.106
	Errors	0.08	0.73	> 0.47	-0.006
Target distance	Runs	-0.51	-5.48	**< 0.001**	0.254
	ITTs	0.32	3.09	**0.04**	0.091
	Switch costs	0.50	5.23	**< 0.001**	0.237
	Errors	0.15	1.35	> 0.18	0.009
Intersections	Runs	0.45	4.59	**< 0.001**	0.191
	ITTs	0.46	4.76	**< 0.001**	0.203
	Switch costs	0.09	0.80	> 0.43	-0.004
	Errors	0.30	2.83	0.09	0.076
PAO	Runs	-0.51	-5.44	**< 0.001**	0.252
	ITTs	0.30	2.93	*0.07*	0.082
	Switch costs	0.53	5.71	**< 0.001**	0.271
	Errors	0.16	1.51	> 0.13	0.015

Note: B = Standardized β, p_{corr} = p values corrected for multiple comparisons. PAO = percentage above optimal. Significant *p*-values are displayed in bold. A *p*-value approaching significance is shown in italics. All DF = 84.

5.5 Discussion

The aims of this study were threefold: First, to investigate how foraging organization changes with increasing age. Second, to study the differences between foraging organization in an easy feature foraging task and a difficult conjunction foraging task, and third, to estimate the connection between foraging organization and other aspects of foraging abilities.

5.5.1 Foraging organization increases with age

We found that organizational abilities increase with age in both feature and conjunction foraging based tasks. In both tasks the pattern of improvement is the same, a gradual increase of organizational abilities from the youngest participants and until adulthood on three out of four measures: best-r, intertarget distance, and PAO. The best-r is a measure of how systematical the travelled path is in each trial, when the path goes systematically in columns or rows from e.g. left to right, or top to bottom, the best-r is high. If there is no evident structure in the travelled path the best-r will be low. On average, the older participants were more systematic in their foraging than the younger age groups. The intertarget distance for the older participants was also shorter, and their surpassing of the shortest possible path through the display lower. There

were also age differences in the number of intersections per trial, but unlike the other measures, they seem to level off by 7th grade, or at the age of 12. To summarize, the 1st and 4th grade participants have the least structured foraging paths, with more instances of the path intersecting itself than the older age groups, resulting in longer intertarget distances and a high PAO. The travelled path continues to become more structured and shorter between age groups, with the adults being the most organized foragers. These results are in accordance with a study by Woods and colleagues (2013) who found a gradual increase in organizational abilities of children aged 2-18 years completing a paper and pencil cancellation task, which slowed down considerably by the age of 12.

Previous studies using PAO or other forms of optimal path analyses, have found that people are remarkably efficient in finding the optimal path through a display (MacGregor & Ormerod, 1996; MacGregor et al.,1999; Wiener et al., 2006). Finding the optimal path is known as the travelling salesman problem in mathematics and computer science, and is an np-hard problem, meaning that there is no efficient way of reaching a solution (Graham et al., 2000; Wiener et al., 2006). In previous studies on the travelling salesman problem, people rarely surpass the optimal path by more than 10%, regardless of the number of items in the path (Graham et al., 2000; MacGregor & Ormerod, 1996, MacGregor et al., 1999; Vickers et al., 2003; Wiener et al., 2007). In the current study, the PAO's of adult participants were on average around 20% for feature foraging but around 50% for conjunction foraging. Here, we didn't specifically ask our observers to take as short a path as possible, but to perform the task quickly without making errors, resulting in longer paths than are known in the aforementioned travelling salesman studies. Regardless, the PAOs of adults are about 20% lower than those of 1st grade children in both foraging tasks, showing that as organizational abilities mature, people start to, perhaps subconsciously, optimize the path through the display.

5.5.2 Differences between feature and conjunction foraging

Organization was better for feature than conjunction foraging for all age groups, on three of the four measures. There was no difference between the number of intersections during feature and conjunction foraging, but the best-r was higher, intertarget distance lower, and the PAO lower in the feature foraging task. There was no interaction between age and foraging task, which means that the differences between feature and conjunction foraging organization are stable throughout development.

Notably, our results reveal differences in organization by age, even for feature foraging. This contradicts the proposal that abilities to detect a target that differs from distractors on a single feature are fully developed by birth or very early in development. According to our data the development of this ability happens gradually with age. Among other things this shows the sensitivity of this foraging task to performance aspects of visual attention, and how it provides additional information above single target search tasks.

Studies on different aspects of foraging performance, such as foraging speed and accuracy, have showed similar results regarding age and task differences. Previous studies have found that both feature and conjunction foraging abilities are still developing up until around the age of 12 (Ólafsdóttir et al., 2019, 2020), but nevertheless, children‘s performance is better for feature than conjunction foraging tasks, as is the case for adult participants. Conjunction foraging is both less accurate and slower than feature foraging. Furthermore, both children and adults seem to refrain from switching between target types during conjunction foraging. When switches do occur, large switch costs appear, that is, participants slow down or hesitate before selecting a target that is different from the previous target, compared to when they select a target of the same type as the previous one (Kristjánsson et al., 2014; Ólafsdóttir et al, 2019; 2020). This has been explained by increased mental load during conjunction foraging compared with feature foraging, especially with regard to working memory, and could be the reason for less organized conjunction foraging. Wiener et al. (2007), found that clearly marking the target locations in their real-life travelling salesman task, diminished the PAO considerably. When participants were handed a “shopping list” with between 7 and 9 figures and asked to navigate between these target items in a room filled with 25 pillars, all marked with different figures, the PAO was on average 8.7, but went down to 2.7 when the target pillars were clearly marked, removing the need to memorize and look for the items from the shopping list. The lower mental load for feature than conjunction foraging could therefore explain the differences in performances between the two tasks.

5.5.3 Why is conjunction foraging less organized?

Differences between feature and conjunction foraging performance can in most cases be explained by differences in mental load and this could apply to organization as well. Another explanation could be that participants treat the conjunction foraging display as two separate search arrays, first looking for all targets of one type, and then the other. These two separate foraging paths could be highly organized but treating them as a single path in all analyses

would result in low scores on all measures. A large part of the conjunction foraging trials was indeed completed in only two runs, and the mean run number during conjunction foraging was low for most age groups. This might indicate that the trials that were completed in over two runs result from a target or two being missed and then collected later, when all other targets had been tapped.

We tested this hypothesis by analyzing the different target types separately, calculating new best-r and PAO scores. We found that the best-r improves considerably for all age groups and that the PAO scores improve for all ages, except adults. The best-r calculated from the separated target types even surpasses the best-r of feature foraging for the 7th grade children, but there are no other significant differences between the best-r of feature foraging and the separated conjunction foraging. The results were similar when PAO was calculated separately for each target type per trial. The PAO of the separated conjunction foraging trials is considerably lower than the overall PAO in the conjunction task and comparable to the PAO of feature foraging trials in four out of five age groups. The PAO of adults does not change when the target types are separated.

Separating the conjunction trials seems to affect children‘s performance more than adults, since children tend to complete these trials in fewer runs than adults (see Table 14). Children may be more prone to consider these trials as two separate foraging paths. Previous studies have shown that a small proportion of adult participants switch as frequently between target types in conjunction as in feature foraging, and their switch costs are minimal (Kristjánsson et al., 2014; T. Kristjánsson et al., 2018; Jóhannesson et al., 2017). This may reflect a willingness to expend more mental effort rather than superior foraging abilities, because adding time limits to foraging tasks results in increased switching and lower switch costs in conjunction tasks for all participants (Á. Kristjánsson et al., 2018). The foraging tasks in the current study are simplified versions of the tasks administered in previous studies. It is therefore possible that some of the adults in the current sample, even a higher proportion than in earlier studies, did not treat the conjunction task as two separate search paths, but switched often between target types. Separating the different target types in the analyses should therefore not benefit those participants, lowering the scores from these analyses for the adult group as a whole.

5.5.4 Does organization influence other aspects of foraging?

We found that organization was not only connected to conjunction foraging, but also feature foraging, in terms of speed, the number of runs, and switch costs. In the conjunction foraging task, these measures were connected with every organizational measure used in the study, and in the feature foraging task, every measure except from the number of intersections. This differs from findings that organizational abilities are only connected to performance in conjunction search but not feature search in single target search (Woods et al., 2013). A variety of cognitive processes underlie performance in visual foraging tasks. These results indicate that organizational abilities play an important role in visual orienting and thus influence other aspects of foraging abilities.

Previous foraging studies have shown age differences in feature foraging (Gil-Gómez de Liaño et al., 2018; Ólafsdóttir et al., 2016; 2019; 2020), and a connection between feature foraging and executive functions (Ólafsdóttir et al., 2016; 2019; 2020; Quirós-Godoy et al., 2018), both of which are in contradiction with findings from single target search tasks, where the differences between children and adults' feature search performance have been negligible (see e.g. Gerhardstein & Rovee-Collier, 2002; Hommel et al., 2004; Thompson & Massaro, 1989; Trick & Enns, 1998; Woods et al., 2013). In the current study, these finding have been extended to organizational abilities.

5.5.5 Summary and conclusions

Our study shows age differences in the movement patterns throughout foraging displays, where increased organization is concurrent with rising age, in both feature and conjunction foraging paradigms. Additionally, foraging organization is connected to other aspects of foraging abilities in both foraging tasks, highlighting its importance in successful visual orienting. Feature foraging is more organized than conjunction foraging in childhood, adolescence, and adulthood. This can either be an indicator of a higher mental load during conjunction foraging or of participants treating each conjunction foraging trial as two separate search paths. Our analyses indicate the latter, but a new study, with only a single target type may be needed to determine the differences between feature and conjunction foraging organization with more certainty. Ideally, a longitudinal study of various foraging abilities of children should be conducted to gain greater insight into how these abilities and the relationship between them develop.

To conclude, organization seems to play a big part in the development foraging abilities and is a promising avenue for further research.

6 Discussion

The main goals of the three papers in this thesis were twofold. The first goal was to gain insight into the development of visual attention by measuring various aspects of foraging in children of various ages and compare them with the foraging of adults. The second goal was to assess whether foraging abilities are in any way related to executive functions, and if so, in what way.

6.1 Age differences in foraging

We found age differences in all aspects of foraging behavior included in this project. For most measures, there was rapid improvement in foraging from early childhood until the middle school years, which leveled off at around 12 years of age when children had reached adult levels of performance. Other aspects of foraging abilities continued to develop until adulthood, such as how often observers switch between target types and foraging organization.

6.1.1 Runs

The number of runs during feature foraging changes drastically between the preschool and middle school years. Paper I revealed that contrary to studies using single target search tasks, which claim that the processes responsible for feature-based processing should be mature by infancy (Adler & Orprecio, 2006; Bertin & Bhatt, 2001; Bhatt et al., 1999a, 1999b; Gerhardstein & Rovee-Collier, 2002), young children have difficulty foraging for targets based on a single feature. This is evident from feature foraging trials completed primarily in two runs, which indicates a tendency to refrain from switching between target types due to a high mental load. Trials completed in only two runs are common for observers of all ages when they are completing conjunction foraging trials, which heavily tax attentional abilities.

Interestingly, when we simplified the foraging paradigm by reducing the number of items on the screen by half, we saw an increase in runs between adolescence and adulthood, which is not apparent when the task is more difficult. In paper I there were no differences in the number of runs between children aged 11 to 12 and adults, but in paper II, where there were only 40 items on the screen compared to 80 in the previous study, there was a slight, but significant increase in the mean number of runs between 15-year-olds and adults. Reducing the number of items in the display lowers attentional load,

which is evident from the lack of a two-trial peak in the run distribution of the youngest participants in paper II (see figure 22). The distribution of the number of runs was close to being normally distributed for all age groups, but shifted slightly to the right with increasing age, indicating an increase in run number with age. The significant difference in run number between the fifteen-year-olds and adults might be explained by a slight two trial peak in the adolescent data. This peak is due to a few participants that tended not to switch between target types, while other participants switched at random.

There have been some speculations that the number of runs does not reflect foraging abilities but rather a strategy choice. Studies on adult participants have shown that by changing the task parameters, it is possible to alter participants' run behavior. T. Kristjánsson et al. (2018) for example, found that adding time limits to the foraging task, resulted in participants switching more often between target types in the conjunction task, and switch costs being lower. Moreover, the shorter the time limit, the more frequently observers switched, and the the switch costs became lower. Another study by Wolfe et al. (2019) found that by only rewarding switches between target types it was possible to increase switching substantially.

Although there is evidence pointing towards run number in conjunction foraging being a choice rather than dependent upon some mental ability in adults, the same might not apply to young children. Factors such as young children's tendency to refrain from switching in a more attentionally demanding feature foraging task, but not in the simpler version administered in paper II (see figure 22), and the existence of switch costs in the feature foraging of young children but not older children and adults, indicate that foraging for targets defined by only a single feature does tax the attentional abilities of young children more than previously believed. These results highlight the importance of studying visual attention with a variety of different tasks and establish foraging as an important tool in visual attention research. The use of single target search tasks has masked these effects because studying target switching abilities, such as runs and switch costs is impossible with these tasks.

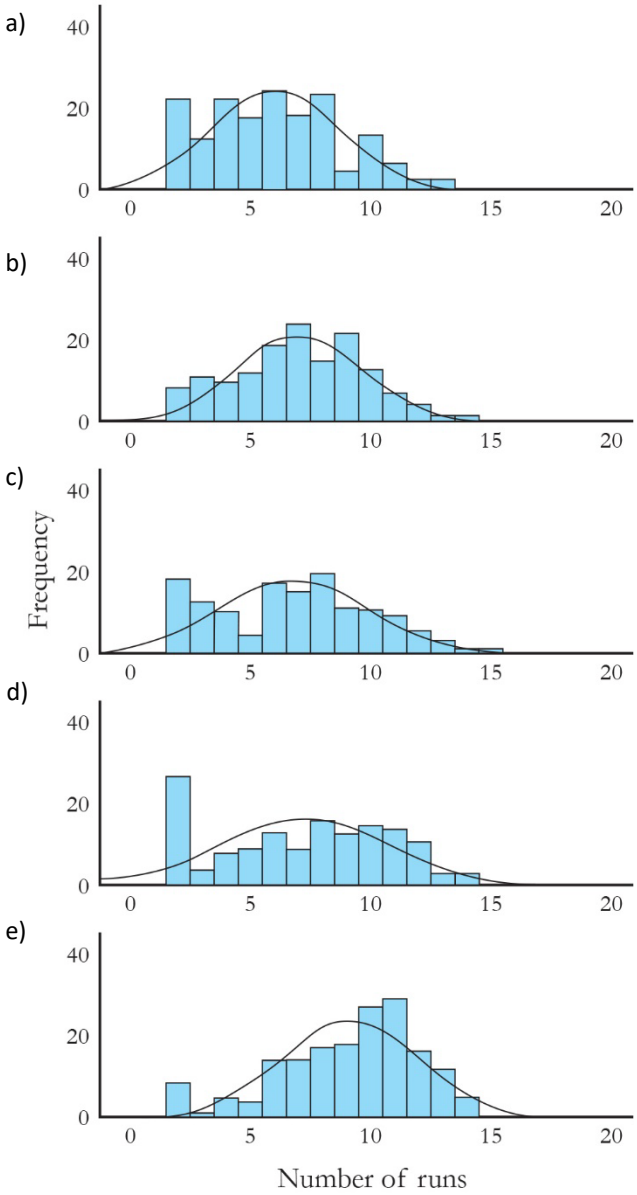

Figure 22. The distribution of the number of runs in feature foraging for each age group in paper II. **Panel a)** = six year old participants, **panel b)** = nine year olds, **panel c)** = twelve year olds, **panel d)** = fifteen year olds, **panel e)** = adult participants. The distribution shifts rightwards with age, but no distinct peaks at two runs can be seen in the youngest participants.

6.1.2 Foraging speed

As would be expected, intertarget times (ITTs) decrease with increasing age. Children reach the same foraging speed as adults at around age twelve in both feature and conjunction-based tasks. Even though younger children's foraging is slower than older children's and adults', the ITTs follow the same pattern throughout the trial to a large extent. Using foraging tasks, we have seen that throughout the largest part of each trial, there is little to no difference in the ITTs of feature and conjunction trials (T. Kristjánsson et al., 2020a; Ólafsdóttir et al., 2016; paper I). The main difference stems from distinctive peaks by the end of each trial, as well as mid peaks in conjunction trials that reflect switch costs, as observers switch to the next target when the first one has been exhaustively collected. These peaks are apparent in the feature foraging of young children in paper I (see also Ólafsdóttir et al., 2016) and are the main thing that sets ITT patterns of young children apart from those of their older counterparts. As mentioned above, these switch costs are only apparent in the foraging of the youngest participants and indicate their difficulty with feature foraging. The mid and end peaks of the younger children are also much larger than those of older children and adults, again reflecting developmental differences in foraging abilities.

The reason for the end peaks that appear in both feature and conjunction foraging tasks in observers of all ages is still unclear. There have been speculations about inhibition of return causing observers to take a long time to refocus their attention to a previously searched area. Although this effect is generally believed to span only a millisecond scale (Briand et al., 2000; Klein & MacInnes, 1999) studies have found slowed responses to previously searched locations in foraging tasks where responses take seconds instead of milliseconds (Thomas et al., 2006). Another possible explanation is that we tend to plan target selection, or the path we will take through the display, by a few targets ahead of time (Tagu & Kristjánsson, 2020). If a target has been missed, it is not in the planned path and when observers reach the end of the path they have planned through the foraging display, but the trial doesn't end, quick scanning of the whole display is needed to find the last target, which will take longer than previous, planned, target selections.

The fact that throughout the largest part of trials, there are little to no differences between collection rates of targets in feature and conjunction foraging tasks is problematic for two-stage processing theories of visual attention. These results contradict accounts of parallel feature processing and serial feature binding (e.g. Treisman & Gelade, 1980; Wolfe, 1994), since

target collection is just as quick when observers are allegedly going through a serial search process, binding together different feature dimensions. Again, these results highlight the usefulness of foraging studies of visual attention.

6.1.3 Organization

In tasks with multiple targets simultaneously present in the display, it is possible to measure how organized the movement pattern through all target items is. Do the observers systematically move through the display while collecting target items, or do they go back and forth in a disorganized path, repeatedly crossing and recrossing their previously travelled path? How does task difficulty affect foraging organization, and does organization increase with age? Organization has not been studied much in healthy populations and little is known about how it develops. Pureza et al. (2013) investigated the cancellation path of children aged six to twelve and found that only a little less than half of the children aged six to ten used organized search strategies, but 78% of the eleven to twelve-year-old children did. In their paper, they did not disclose how they defined and measured search organization. Similarly, Woods et al. (2013) found that organization, as measured with best-r, intersections, and intertarget distances, increased linearly from ages two to twelve, where it leveled off until age eighteen. In paper III we found that foraging organization increases from age six up until adulthood in three out of four measures, not only in the more attentionally demanding conjunction foraging task, but also during feature foraging.

Although feature foraging organization continues to develop up until adulthood, it is more organized than conjunction foraging in every aspect measured except from the number of intersections. We found that this was not due directly to the increased attentioal load characterizing the conjunction foraging paradigm, but rather to the fact that observers treat the conjunction task as two separate paths through the foraging display, one consisting of red discs and the other of green squares (or vice versa). Separating these two paths and finding their mean resulted in the same level of organization as found in the feature foraging task.

Lastly, we found that organizational abilities are connected to other foraging measures, perhaps indicating that visual attentional abilities are somehow dependent upon organizational abilities, as posited by Woods et al. (2013), or that both of these aspects of foraging involve some other cognitive process or processes, such as executive functions.

6.2 Foraging and executive functions

We have found that executive functions are connected to foraging abilities in both children and adults. Interestingly, and in accordance with our findings of age differences in feature foraging abilities, we found relations not only between executive functions and conjunction, but also feature, foraging.

6.2.1 Differential connections between different ages

The relationship between foraging and executive functions changes with age. In paper I we found that attentional flexibility and working memory, but not inhibition, are connected to both foraging speed and switch costs, but not the number of runs. Moreover, these connections differed between eleven to twelve-year-old children and adults. ITTs were connected to attentional flexibility in children but working memory in adults. Likewise, switch costs were connected to both attentional flexibility and working memory in children but were not connected to any EF component of the adults. In a previous study on young children's foraging, we found that ITTs are connected to both verbal working memory and a global measure of self-regulation called the Head-Toes-Knees-Shoulder task (Ólafsdóttir et al., 2016). In that task, the children are asked to touch for example their knees but have to inhibit the prepotent response to obey and touch their shoulders instead. After a while, the rules are changed and now the shoulders are paired with the toes and the knees with the head. This task taxes all core components of executive functions: The children have to inhibit a prepotent response, switch between different rules, and keep the rules and appropriate responses in working memory. Taken together, the results from these studies indicate that since components of executive functions develop on different trajectories (see e.g. Anderson, 2002), children rely on the processes that have been established to complete the foraging task. Similar results have been found in studies relating the core components of EF with complex tasks, such as the ToL (Senn et al., 2004) and WCST (Huizinga & Van der Molen, 2007). Young children rely primarily on inhibition, whereas in middle childhood the main emphasis is put on attentional flexibility, and by adulthood this focus has moved over to working memory.

6.2.2 Executive functions account for age differences in foraging

In paper II we used a different approach to measure the connection between executive functions and foraging. Partial least squares – structural equation modeling (PLS-SEM) is a dimension reduction method where variance is estracted into latent factors and causal effects between them are estimated (Ali et al., 2018; Hair et al., 2019; Ringle et al., 2020). This method is

recommended when measures are highly correlated and does not require extensive datasets like more traditional SEM modeling techniques. Due to multicollinearity of our EF data, we loaded all EF measurements onto a single latent factor which we used to estimate the connection between EF and foraging, over and above age effects. We found that most of the age differences in foraging performance found in that study were due to indirect effect through executive functions, that is, the development of executive functions accounts for a large majority of age differences found in foraging abilities.

7 Conclusions

Throughout the three studies underlying this thesis, we have repeatedly found age differences in foraging, not only in the more difficult conjunction foraging task, but also during simple feature foraging. Those results contradict findings from single target search tasks and argue against they hypothesis that feature processing ability is mature in infancy (e.g. Adler & Orprecio, 2006; Bhatt et al., 1999a, 1999b; Gerhardstein & Rovee-Collier, 2002).

Moreover, using foraging tasks, we have seen that two stage processing models of visual attention (Treisman & Gelade, 1980; Wolfe, 1994) may not accurately represent attentional orienting over time. Throughout the majority of each foraging trial, there were little to no differences between the foraging speed in feature and conjunction tasks, arguing against accounts of parallel feature processing and serial and time-consuming feature binding.

Lastly, we have found that foraging is highly dependent upon EF, where age differences in foraging are to a large extent mediated by executive functions, and at different stages in development, observers rely on different components of EF to tackle the foraging tasks set before them.

All of these results in combination highlight the importance of studying visual attention from various angles, using different methods. The foraging task is a highly useful task for studying attentional orienting over time since it is both dynamic and easy to administer and yields rich datasets with next to endless possibilities of paradigm variations.

7.1 Future directions

There are still many unanswered questions regarding foraging and executive functions. To be able to model multigroup comparisons with PLS-SEM and obtain greater insights into the differential connections between EF and foraging throughout development, the next step would be to conduct a large study on foraging and EF, with at least 40 persons in each age group. Another way, and even more ideal, would be to conduct a longitudinal study, perhaps with a sequential cohort design to see how these abilities and the relations between them develop.

Another interesting question that remains unanswered is the connection between foraging organization and EF. Some researchers seem to equate

these two constructs (see e.g. Benjamins et al., 2019; Woods et al., 2013), while other studies claim that they are separate functions (Ten Brink et al., 2017). A cross-sectional study on the connection between organization and EF is already underway.

Last but not least, foraging studies in a more ecologically valid environments, such as in the form of a 3D computer game (Prpic et al., 2019) and a virtual reality environment (Kristjánsson et al., 2020) have already been conducted on adult observers and would be ideal for further research into the development of foraging abilities and visual attention.

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